Infants’ Representation of Objects and Substances:

Three Experiments on the Core Principles of Rigidity and Cohesion

Thesis

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Den Stoff sieht jedermann vor sich, den Gehalt findet nur der, der etwas dazu zu tun hat, und die Form ist ein Geheimnis den meisten.

Johann Wolfgang von Goethe (1749 - 1832), Maximen und Reflexionen

ABSTRACT

A physical entity can be represented either as an individual kind, or as a substance kind, whereby identity is only ascribed to the individual kind. This thesis examined these kinds of representations in infancy. Two main properties of a rigid object, which is typically represented as an individual kind, constituted the core of the thesis: the rigidity of the object (i.e., guaranteeing its stable shape) and the cohesiveness of the object (i.e., guaranteeing its internal connectedness). However, non-rigid or non-cohesive physical entities are not necessarily represented as a substance kind. This means, non-solid substances or collections of objects may well be represented as, for instance, drops of water or flocks of birds. Even infants' representation of individual kinds is not restricted to rigid objects, but extends to collections of objects (Wynn, Bloom, & Chiang, 2002) or portions of a deformable substance (Huntley-Fenner, Carey, & Solimando, 2002). Yet the exact natures of the processes that promote an individual-based or a substance-based representation in infants remain unclear.

Three studies examined the effects of non-rigidity and non-cohesiveness on 8- to 12-month-old infants' representation of physical entities. This was based on measures of infants' visual attention (i.e., looking time in Study 1, duration and location of gazes in Study 2) and on action-based measures (i.e., manual search in Study 3). Additionally, an unmodified version of Study 2 was conducted with adults.

Taken together, the results of these studies demonstrated that unambiguous spatiotemporal information (e.g., two well-defined groups) but not featural information (e.g., shape) enables infants to represent non-rigid and non-cohesive

entities as individual kinds. At the same time, spatiotemporal information prevented infants from maintaining such representations if this information did not appropriately mark individuals. Furthermore, individual-based processing was subject to a limitation set by the number of objects in a collection. That is, infants' representation was individual-based in the case of small collections but substance-based in the case of large collections.

These findings add to the infancy literature, and further highlight the parallels to adults' representation of individuals and substances. That is, similar to the current findings adults' processing of individuals is based primarily on spatiotemporal information, as well as it is subject to a set size limit (vanMarle & Scholl, 2003).

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1. INTRODUCTION

The physical world can be classified into objects with shape and identity and substances without shape and identity (Au, 1994; Prasada, Ferenz, & Haskell, 2002; Wellman & Gelman, 1992). Prototypical objects are bounded, solid bodies that allow judgments of numerical identity ("this is the same ball"). Prototypical substances are unbound, non-solid materials (e.g., liquid, gels, or granules such as sand) that do not allow judgments of numerical identity ("this is the same snow").

Cohesion, continuity, and contact form the core principles of infants' knowledge about the physical behavior of objects (Baillargeon, 2008; Carey & Spelke, 1994; Gopnik & Wellman, 1994; Leslie, 1994; Spelke, 1990, 1994; Spelke, Breinlinger, Macomber, & Jacobson, 1992; Wellman & Gelman, 1992). For instance, very young infants expect an object to move as a connected whole (i.e., cohesion, see Spelke, Breinlinger, Jacobson, & Phillips, 1993), to be a solid, enduring entity (i.e., continuity, see Baillargeon, Spelke, & Wasserman, 1985), and to influence the motion of another object only through physical contact (i.e., contact, see Leslie & Keeble, 1987). Sensitivity towards physical laws, which can not be derived from these principles, appear only later in development (e.g., gravitiy, see Spelke, Katz, Purcell, Ehrlich, & Breinlinger, 1994).

Due to their loose internal connectedness, non-solid substances violate the core principle of cohesion. The same holds for the physical behavior of collections of objects (e.g., a flock of birds, Chiang & Wynn, 2000). These physical properties are reflected in many natural languages as expressed in the labeling of objects with count nouns and the labeling of substances with mass nouns. Substances lack a consistent structure and do not form discrete, countable entities. Mass nouns, therefore, can only be indirectly individuated and pluralized (e.g., two *liters* of milk, many sand*castles*, or one *pile* of gravel) (Papafragou, 2005). However, whether a mass or count syntax is appropriate or not is not fully provided by the entity itself, and is at least partly dictated by semantics. For instance, while some collections are labeled with a mass noun (i.e., substance, e.g., rice), in other cases it is the constituent element that is labeled (i.e., objects, e.g., beans) (Bloom & Kelemen, 1995; Middleton, Wisniewski, Trindel, & Imai, 2004; Wisniewski, Lamb, & Middleton, 2003). Moreover, the labeling of such entities is not congruent between languages (e.g., in German *Laub*, in English *leaves*) and many languages even use mass nouns to label all inanimate, physical entities (e.g., Chinese and Japanese) (Imai & Gentner, 1997; Imai & Mazuka, 2007; Li, Dunham, & Carey, 2009; Smith, Colunga, & Yoshida, 2003). Finally, adults' perception often does not follow a restrictive dichotomy of object or substance. For instance, on the one hand one can perceive a cloud as an individual kind despite its lack of enduring individuality (i.e., prototypical non-solid substance), and on the other one can describe the wood of a chair (i.e., a prototypical object).

Driven by the continuing insights generated by the study of object-substance classification, scientific research has increased greatly in recent years. Essentially, knowledge of material properties is a prerequisite for successful interaction with the physical world. For instance, a child needs to learn that she or he cannot grasp water, or that she or he cannot force themselves through a narrow, rigid opening. Furthermore, a large body of research has demonstrated the ease with which the count and mass noun distinction is learned during language acquisition. This may be rooted in existing preverbal distinct representations of objects and substances (Bloom & Markson, 1998; Colunga & Smith, 2008; Dickinson, 1988; Hall, 1996; Soja, Carey, & Spelke, 1991; Subrahmanyam, Landau, & Gelman, 1999). Likewise, this research may foster our understanding of the comparability of the world in the minds of infants and adults.

1.1 Objects

A large body of research has been devoted to the class of prototypical objects (i.e., rigid, bounded bodies), and a comprehensive summary would exceed the scope of this thesis. The first part of this chapter thus introduces the methodological approaches and basic findings that are central to the study of object-substance classification. The second part introduces the theoretical and methodological approaches to adults' representation of prototypical objects.

Object permanence—expecting an object to continue its existence even when it is out of view—has been the central paradigm underlying the investigation of infants' object concept since Piaget's seminal work (1954). In contrast to Piaget's claim that infants are unable to represent objects that are not currently perceptible, it is now largely confirmed that very young infants do represent objects as continuously existing entities (Aguiar & Baillargeon, 1999, 2002; Baillargeon, 1986; Baillargeon et al., 1985; Spelke et al., 1992; Xu & Carey, 1996). Moreover, young infants represent objects as unique individual kinds (Krojgaard, 2004; Leslie & Káldy, 2001; Spelke, Kestenbaum, Simons, & Wein, 1995; Wilcox & Baillargeon, 1998b; Xu, 1997). The latter conclusion is drawn from studies typically presenting infants with a scenario like that depicted in Figure 1.

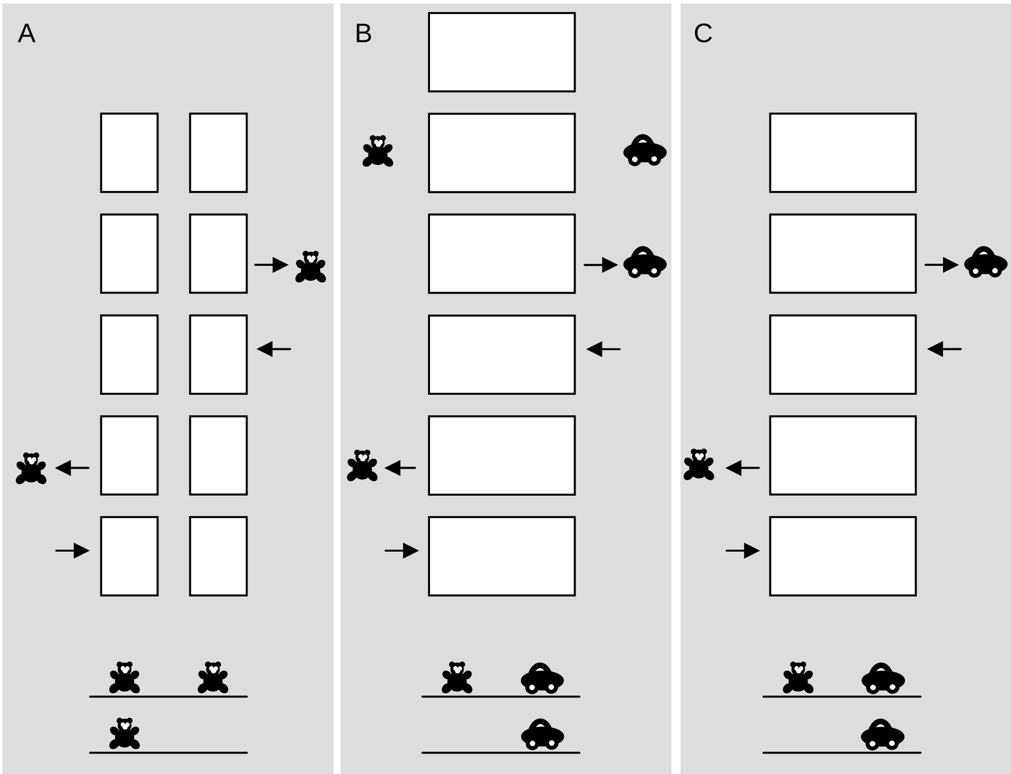


Figure 1. Individuation based on spatiotemporal information (A and B) or featural/kind information (C) (adapted from Xu & Carey, 1996, pp. 113-126).

Infants are familiarized with an object that repeatedly disappears behind an occluding screen and an object that repeatedly appears from a second occluding screen. Following this familiarization, infants' looking times at an expected outcome are compared with the looking times at an unexpected outcome. In the study by Xu and Carey (1996) 10-month-old infants succeeded (i.e., demonstrated enhanced interest towards the unexpected outcome) in events where spatiotemporal information was provided. That is, Figure 1 shows that no object appears in-between the two occluding screens in event A. Consequently, spatiotemporal information marks the presence of two objects. The same holds for event B. Two objects must be involved in this event, because a single object cannot be in two places at the same time. By contrast, infants did not differentiate between the expected and the unexpected outcome in event C. Here, the number of objects has to be inferred on the basis of featural/kind information (i.e., a bear cannot be a car at the same time).

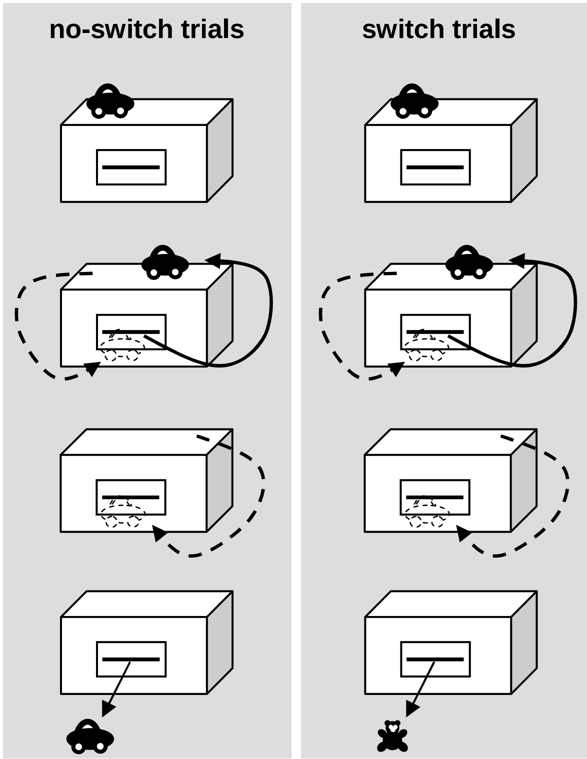


Figure 2. Object individuation in a manual search task (adapted from Xu & Baker, 2005, p. 312).

The primacy of spatiotemporal over featural (e.g., shape, texture, color) or kind information (e.g., animal/vehicle) has been replicated in a number of looking-time studies (Káldy & Leslie, 2003; Krøjgaard, 2003; Needham, 1998; Tremoulet, Leslie, & Hall, 2000; Wilcox, 1999; Wilcox & Baillargeon, 1998a; Woods & Wilcox, 2006; Xu, Carey, & Quint, 2004; Xu, Carey, & Welch, 1999), and in more recent studies employing a manual search task (Kingo & Krøjgaard, 2011; Van de Walle, Carey, & Prevor, 2000; Xu & Baker, 2005). In these action-based tasks, the experimenter takes out an object (e.g., a car) from a box, presents it to the infant and places it back inside the box (see Figure 2). Next, infants' reactions towards an expected and an unexpected event are compared. In both events the infant is allowed to search the box for the hidden object. However, while she or he finds the original object in the expected events (no-switch trial), the original object was secretly replaced by another object in the unexpected event (switch trial). Finally, infants are allowed to re-search the box for a second time. This re-search time is typically longer if infants infer the continuance of the original object in the box in switch trials.

In sum, research on infants' object individuation demonstrates an early appreciation of an object as a distinct physical body obeying spatiotemporal laws, while its features are perceived as critical only later in development.

Theories of adults' representation of objects are based on observations of which the following is an example. Observers can easily track an object's persistence over time even when both lower-level visual features and higher-level object kind change. For instance, one might first mistake an object approaching from a distance as a black (low-level visual feature) bird (high-level object kind), and only from closer up recognize it as a blue plane. Despite the changes in both feature and kind in the proximity of perspective, the perception of the individual object remains uninterrupted. This observation led to the notion of an intermediate level of representation specifically designed to track objects (e.g., object files, Kahneman, Treisman, & Gibbs, 1992; FINST's, Pylyshyn, 2001). This system establishes indexes connected to discrete objects in the visual field, the indexes remaining attached to the objects when they move through space similar to a pointer (FINST = *fin*gers of *inst*antiation). These indexes are predominantly based on spatiotemporal information. Therefore, featural changes (e.g., plane/bird) do not per se necessitate the establishment of a new index. Equally, this index remains active over short periods of occlusion (e.g., disappearance behind another object) (Mitroff, Scholl, & Wynn, 2004). Two experimental paradigms illustrate the existence of such indexes: The multiple-object tracking paradigm (MOT) and the object-reviewing paradigm.

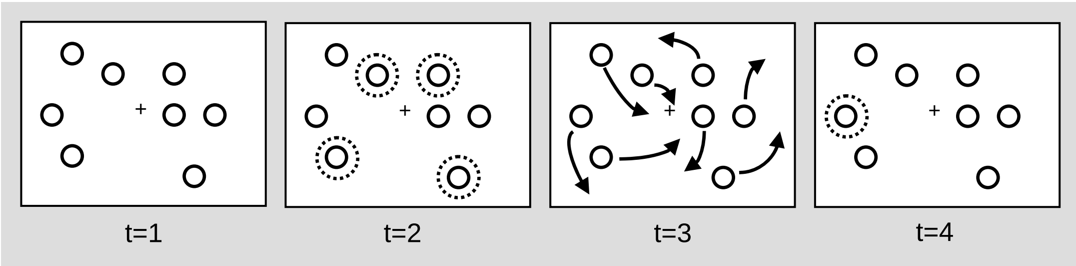
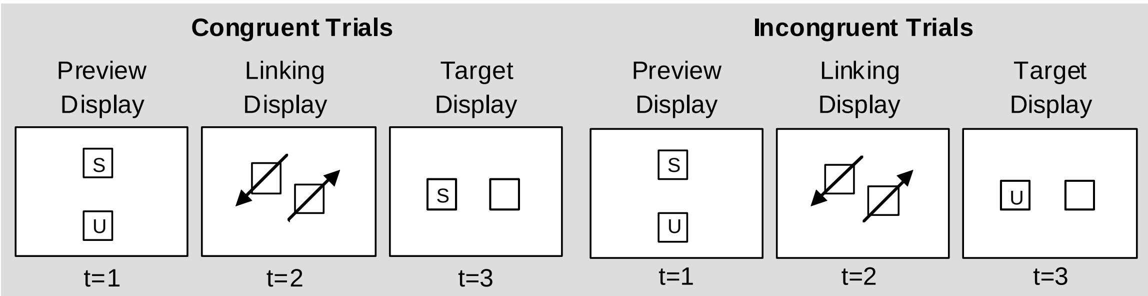


Figure 3. Multiple-object tracking task (adapted from Pylyshyn, 2001, p. 142).

In a MOT task several identical, static objects are presented on a computer screen (see Figure 3, t=1). A subset of these objects is then highlighted as target items (t=2), the task being to track them when all the objects (targets and distractors) move randomly and independently across the screen (t=3). Finally, the target items need to be identified again once all the objects have stopped moving (t=4) (Pylyshyn & Storm, 1988). Whereas prior theories were based on the assumption that adults' attention only focuses on locations (see Cave & Bichot, 1999, for a review), in a MOT task the target and distractor items incidentally spatiotemporally overlap, demonstrating that attention can indeed also focus on individual objects. The MOT task therefore offers a distinctive measure of adults' tracking of individual objects (Cavanagh & Alvarez, 2005; Scholl, 2009).

In the object-reviewing paradigm, distinct letters appear briefly within static objects (see Figure 4, t=1). The letters are removed and the objects shift within the display and then stop (t=2), whereupon one single letter reappears on one of the objects (t=3), the task being to vocally name the letter as quickly as possible (Kahneman et al., 1992). Typically, response times are more rapid when the final letter matches one of the initial letters. However, response times are even quicker if the letter appears on the same object within which it initially appeared. As in the MOT task, this shortening of response times cannot be based on the representation of locations, because the object has been displaced, meaning that the more rapid identification has to be based on the representation of individual objects (i.e., object-



specific preview benefit—OSPB).

Figure 4. The object-reviewing paradigm (adapted from Mitroff, Scholl, & Wynn, 2005, p. 69).

In sum, both the MOT task and OSPBs offer adequate measures of adults' tracking of individual objects. Therefore, these measures can be used to address both *what* visual stimuli are tracked in terms of individual kinds, as well as *how many* individual kinds adult observers can track.

Set against the findings outlined above for infancy research, it can be summarized that similar measures can be established in the two fields, the concurrence being that in infancy research looking-time tasks and manual-search tasks can likewise be applied to examine both *what* visual stimuli are represented as individual kinds, and *how many* individual kinds infants can represent simultaneously. Furthermore, this aspect (the prototypical object) points to initial parallels concerning the nature of object representation, the argument being that both infants' representation of objects and adults' object indexes are (a) predominantly based on spatiotemporal information, and (b) survive periods of occlusion.

1.2 Substances

The study of substance kind representation in infancy has to be based on two premises. First, that infants appreciate that substances are part of the physical world. That is, non-solid substances are represented as substantial matter, occupying space. Second, that substance is represented as constituting an enduring property of a physical entity. Research on infants' representation of the quantity of non-solid substances suggests that these are perceived as substantial matter. For instance, 6-month-old infants anticipate a change in the size of a non-solid substance when more substance is added (Gao, Levine, & Huttenlocher, 2000; Hespos, Dora, Rips, & Christie, in press; vanMarle & Wynn, 2011). The same conclusion can be drawn from infants' manual interaction with non-solid substances. That is, 6-month-old infants adjust the performance of distinct actions according to material properties (e.g., slapping liquids/squeezing soft objects) (Bourgeois, Khawar, Neal, & Lockman, 2005; Fontenelle, Kahrs, Neal, Newton, & Lockman, 2007; Rochat, 1987). Moreover, infants perceive that material properties are permanent. That is, infants react with surprise when a rigid object unexpectedly starts to move in a non-rigid manner, and vice versa (Gibson, Owsley, & Johnston, 1978; Gibson, Owsley, Walker, & Megaw-Nyce, 1979; Walker, Owsley, Megaw-Nyce, Gibson, & Bahrick, 1980; see also Aguiar & Baillargeon, 1998; Baillargeon, 1987; Rochat, 1987), or when a liquid unexpectedly starts to move in a rigid manner (Hespos, Ferry, & Rips, 2009; see also A. J. Caron, Caron, & Antell, 1988).

1.2.1 Non-Solid Substances

Non-solid substances have no permanent boundaries and therefore offer no immediate criteria for individuation. However, they can be individuated by the means of an artificial measure (e.g., sips of liquids, shaped portions). Huntley-Fenner et al. (2002) examined whether 8-month-old infants can use such measurements to represent individual portions of a typical non-solid substance , in this case granules, employing an adapted version of the looking-time task introduced in Section 1.1 (Xu & Carey, 1996). Infants sat opposite a stage and observed sand being poured onto an empty surface, finishing in a bounded pile. Next, two clearly separate screens were raised, whereby one of them hid the pile from view. A second amount of sand was then poured behind the second screen, finishing in a second invisible pile. In this event evident spatiotemporal information about the number of individual piles is provided by the second action and the presence of two separate screens (and indeed the lack of sand in-between the two screens). Nevertheless, infants did not react with surprise (i.e., extended looking times) when one pile was surreptitiously taken away and the screens then removed to reveal only the original pile of sand. Because in this task the infants ideally had to represent that something was hidden behind each of the two screens, the actual results not only show an inability to form individual-based representations of sand (i.e., sand piles), but suggest an inability to represent the continued existence of sand in itself—in other words, "a failure of sand permanence" (Huntley-Fenner et al., 2002, p. 219). Comparable findings were revealed in a MOT task related to that in Figure 3, whereby adults were required to track targets that flowed in a similar manner to the motion of sand. It was established that this granular motion disabled participants from keeping track of the individuated portions, and that the identification of target items was at chance level (vanMarle & Scholl, 2003).

The motion pattern of a non-solid substance contrasts to the motion pattern of a rigid object in two respects, each of them properties of the substance itself. First, non-solid substances cannot maintain a stable shape (i.e., rigidity); and second, they cannot maintain internal connectedness (i.e., cohesion, see Huntley-Fenner et al., 2002; vanMarle & Scholl, 2003).

In Huntley-Fenner et al. (2002) non-rigidity prevented the infants from establishing a pictorial representation of an entity, and therefore from predicting the shape of a hidden sand pile. However, infants were in a position to track separate portions of a different non-solid substance. In this case, two blobs of a children's slimy, elastic mixture were similarly lowered to behind two occluding screens, whereby the substance extenuated its shape but remained cohesive as it oozed down to the surface. However, despite the non-rigid motion infants perceived its absence behind the second screen and reacted with measurable surprise. Likewise, adult observers in the study by vanMarle and Scholl (2003) were able to track non-rigidly moving entities (in this case shapes with constantly metamorphosing geometrical outlines) as accurately as rigidly moving objects.

VanMarle and Scholl (2003) suggest that adults' success in tracking non-rigid entities could be based on the spatiotemporal information supplied by the entity: The entity preserves its outer contour during motion and thus provides an opportunity to the observer to fixate a clearly defined space (e.g., the center of the entity), which is stable during the course of motion. By contrast, the motion of sand does not provide the same spatiotemporal information: The autonomous motion of the individual grains of sand does not offer a stable point of reference. Moreover, cohesion violations affect the notion of identity because they disable one from representing a bounded, enduring whole. For instance, if a cup is broken in pieces, does the cup continue to be embodied in one of its pieces or in all of them, or does the cup cease to exist? (Bloom, 2000; Pinker, 1997). Chiang und Wynn (2000) showed that cohesion violations do indeed fundamentally affect infants' ability to build persistent representations. Using Lego bricks, 8-month-old infants failed to persistently represent a pile-like object, which they observed being disassembled into its five constituent parts. Even the most simple cohesion violation (i.e., the splitting of an object into two halves) has been shown to affect infants' representational abilities in a choice task (Cheries, Mitroff, Wynn, & Scholl, 2008). In the baseline condition of this task, a reliable number of 11-month-old infants chose a cup containing a large cracker over a cup containing a small cracker. By contrast, if the infants observed how the large cracker was broken in two halves before being placed inside the cup, only approximately half the infants chose the cup containing the two halves of the larger cracker—equal to chance level. However, there are two possibilities to explain this random choice. First, "the most extreme interpretation of these results would be that the split completely destroyed […] their [the infants'] initial representation" (Cheries et al., 2008, p. 430). That is, infants' representation of the continued existence of the cracker was disrupted (i.e., loss of substance permanence). Second, the fact that the infants did not completely avoid the cup with the broken cracker, but chose it approximately half of the time, suggests that they at least expected *something* to be inside the cup. According to this weaker interpretation, the representation of the cracker therefore outlasts the cohesion violation, but the information about the cracker does not (i.e., cracker-substance, but not size).

Adults' tracking of splitting objects may help to identify the representational losses caused by simple cohesion violation. Mitroff et al. (2004) examined precisely whether object specific information (i.e., OSPB) survives a similar type of cohesion violation in a study, where participants observed depictions of two circles that moved across a computer screen (cf. Figure 4). Whilst one of these circles moved along a straight horizontal line, the other circle divided in two identical circles that moved towards two separate final locations. The analysis of the OSPBs indicated that the cohesion violation did not fully destroy the object representation, but that it placed considerable demands on the visual system. That is, participants were unable to maintain the information about the second, cohesive object. This finding favors the weaker interpretation of the results in Cheries et al. (2008), and suggests that cohesion violation does not have an absolute impact on object representation.

To conclude, in the two studies examining how cohesion violation affected infants' representation of objects, Chiang and Wynn (2000) demonstrated that the splitting of an object into five pieces leads to a complete disruption of representation. However, according to Cheries et al. (2008) it is possible that infants maintain some form of representation (i.e., representation of substance) when an object is broken into two pieces, this in turn being comparable to the findings with adults (Mitroff et al., 2004). The next chapter addresses how infants represent multiple objects, per se, and demonstrates that two pieces may indeed differ fundamentally from five pieces.

1.2.2 Collections

The topic addressed in this section is embodied in the early description of the *un, deux, trois, beaucoup* phenomena when young children learn to count (Descoeudres, 1921; as cited in Strauss & Curtis, 1981)—beyond a particular number an observer is no longer in a position to numerically distinguish the individual items in a collective mass, and whilst being aware that the mass consists of distinct items primarily recognizes only the composite whole.

Previous research demonstrates that distinct representational systems for both small and large collections exist in the preverbal infant. That is, if a collection consists of up to approximately three objects, infants' representation of the collection is based on the individual items (see Cordes & Brannon, 2008; Feigenson, Dehaene, & Spelke, 2004; Wynn, 1998, for reviews). This individual-based representation of collections enables, for instance, 12-month-old infants to search for precisely three hidden objects, or to choose a cup containing one object more than another cup (e.g., 3 crackers over 2 crackers) (Feigenson & Carey, 2003, 2005; Feigenson, Carey, &

Hauser, 2002). However, if a collection contains more than three objects, infants are not able to focus on the individual items, but focus on the collection as a whole (i.e., an approximate number system—ANS) (Brannon, Abbott, & Lutz, 2004; McCrink & Wynn, 2004; Wood & Spelke, 2005; Xu, 2003; Xu & Arriaga, 2007; Xu & Spelke, 2000; Xu, Spelke, & Goddard, 2005). This collection-based representation has been shown to disable infants from searching for precisely four or more hidden objects. Moreover, infants studied by Feigenson and Carey (2005) showed no preference for a cup containing four crackers over a cup containing one cracker (a ratio of 1:4). This finding is all the more striking because their own study has shown that 12-month-old infants can otherwise easily differentiate two quantities with far smaller ratios in small collections (up to 2:3), whilst Xu and Arriaga (2007) have demonstrated the same for large collections (up to 1:2). This paradox could be explained by the fact that such a task involves the individual-based system and the collection-based system interfering with one another, meaning that placing the four crackers one-by-one after each other in the cup induced an individual-based representation. However, four objects exceed the capacity of the system to represent individual items, and it is this overload that was concluded to have led to a loss of information about the hidden objects (Feigenson & Carey, 2005). Despite this, the system overload did not as fully disrupt infants' representation as in the case of cohesion violations (Chiang & Wynn, 2000; Huntley-Fenner et al., 2002). That is, infants reliably chose a cup containing four crackers over an empty cup, which demonstrates that at least the representation of "some cracker-stuff" (i.e., substance) remained intact (Feigenson & Carey, 2005, p. 308).

Beyond representing the individual items that constitute a small collection, given appropriate motion patterns infants are also in a position to represent collections themselves as individuated groups. In the study by Wynn et al. (2002), 5-month-old infants were familiarized with the motion of two or four moving collections. During the course of the following test events the number of collections was either doubled (when two collections were used during familiarization) or halved (when four collections were used during familiarization). The analyses of the looking pattern at these events showed that infants reliably preferred the new number of collections.

These findings are paralleled by adults' perception of collections. First, the ability to track multiple objects among distractors in a MOT task is limited to approximately four objects (Bahrami, 2003; Cavanagh & Alvarez, 2005; Culham et al., 1998; Scholl & Pylyshyn, 1999; Sears & Pylyshyn, 2000; Yantis, 1992). Second, if multiple objects undergo a shared movement these are perceived as individual collections (Bloom & Veres, 1999; vanMarle & Scholl, 2003).

1.3 The Current Studies

Prior research has shown that infants' and adults' representations of rigid objects are fundamentally different from their representations of non-solid substances (Huntley-Fenner et al., 2002; vanMarle & Scholl, 2003). Establishing the distinction itself is one thing, but the origin of this distinction is not readily apparent because, as outlined above, there are at least two differing properties in their respective motion patterns, namely rigidity and cohesion. Table 1 provides an overview of the current state of research and the open questions associated with these properties. Table 1 also arranges previous findings in terms of individual-based and substance-based representations (e.g., collection-based, stuff-based), and in terms of loss of representation (i.e., lack of substance permanence). The numerous parallels in infants' and adults' representations of objects and substances suggest that these actually stem from a similar object representation system (e.g., Cheries, Mitroff, Wynn, & Scholl, 2009; Leslie & Káldy, 2001; Leslie, Xu, Tremoulet, & Scholl, 1998). However, this proposition is based on findings generated from different experimental paradigms. For instance, infants' tasks typically involved a long period of occlusion (see Wynn et al., 2002, for an exception), whereas adults' tasks did not. Consequently, infancy research has addressed short-term- or working-memory capacities (e.g., Feigenson, 2007), while adult research has addressed attentional processes (e.g., Cavanagh & Alvarez, 2005).

With this in mind, the research questions addressed in this thesis have been informed by two underlying aims: First, to define the properties that characterize an entity as either an individual kind or as a substance kind; second, to find measures that enable a comparison between infants' and adults' representation of objects and substances.

1.3.1 Rigidity

The failure to represent sand as a permanent substance was not caused by the non-rigid motion of sand in the study by Huntley-Fenner et al. (2002). However, given the two separate screens used in the study it remains an open question whether the substance was represented as an individuated portion, or whether it was represented as an unbound substance. Furthermore, the study fails to address rigidity violations. Previous studies have shown that infants expect rigid boundaries to remain stable over time (e.g., Gibson et al., 1979). Based on this finding, it could be concluded that only an entity that loses its rigid boundaries over the course of motion conflicts with infants' expectations towards a physical entity, while a non-rigid entity conforms to expectations. In addition, previous research has shown that infants apply these expectations (i.e., persistence of material properties) by demonstrating sensitivity towards the stability of the shape of a rigid object (e.g., Xu & Baker, 2005). However, sensitivity towards the transformable shape of a non-solid substance has not been addressed in previous research.

Table 1

Current state of research on the representation of physical entities as individual kinds, substance kinds, or lack of substance permanence (i.e., representation loss) in infants: Parameters and overlaps

Representation	Physical entity
Individual kind	Rigid object (Xu & Carey, 1996)
	Small collection (Wynn, 1992)
	Bound collection (Wynn et al., 2002)
Overlap	Bound non-rigid (Huntley-Fenner et al., 2002)
	Rigidity violation (Gibson et al., 1979)
Substance kind	Large collection (Feigenson & Carey, 2005)
Overlap	Minor cohesion violation (Cheries et al., 2008)
No substance permanence	Major cohesion violation (Chiang & Wynn, 2000)
	Granule (Huntley-Fenner et al., 2002)

1.3.2 Cohesion

Infants are able to represent the individual objects in a small, non-cohesive collection, but fail to do likewise with large collections (e.g., Feigenson & Carey, 2003; Wynn, 1992). Furthermore, infants may represent large collections as a permanent substance (Feigenson & Carey, 2005), but fail to do likewise when faced with a non-solid substance consisting, for instance, of countless grains (Huntley-Fenner et al., 2002). The study of infants' representation of non-cohesive collections thus implies that the shear number of its constituent elements is significant. The same conclusion can be drawn from studies presenting infants with cohesion violations. Again, while infants may persistently represent a large collection as a permanent substance (Feigenson & Carey, 2005), they fail to do likewise if the collected items originate from a previous single rigid object (Chiang & Wynn, 2000). Finally, it remains an open question whether a cohesion violation that results in a small collection is powerful enough to disrupt infants' representation of an entity (Cheries et al., 2008).

Study 1 here addressed the consequences of non-rigidity and non-cohesiveness on infants' tracking of individuated entities using a habituation task. Eight-month-old infants were presented with computer-animated stimuli with depictions of (a) moving non-rigid or non-cohesive entities, or (b) moving objects that lost rigidity or cohesiveness only in the course of motion. The extent of the cohesion violation was additionally varied by means of the number of the resulting parts. Two pilot studies were undertaken to test the premises that underpin this study. Pilot Study A was undertaken to confirm that cohesion violations do not have an absolute impact on infants' persistent object representations in a violation of expectation task. Pilot

Study B was undertaken to confirm the proposed significance of the number of fragments from a whole in a choice task.

Study 2 examined infants' ability to attend to the individual constituents in collections of varying sizes. The looking pattern of 10-month-old infants was analyzed using an eye-tracking device and compared to adults' looking pattern at the same events.

Study 3 tested 12-month-old infants' sensitivity towards the transformable shape of a non-rigid substance in a manual search task.

2. PILOT STUDIES

Two pilot studies were conducted preliminary to Study 1 in order to verify two critical hypotheses. The first hypothesis states that cohesion violations do not have an all-or-nothing impact on infants' ability to represent the continued existence of an entity (Pilot Study A). The second hypothesis states that the number of fragments of a whole is significant in instances of cohesion violation (Pilot Study B).

2.1 Pilot Study A

This study examined whether a simple cohesion violation (i.e., split in two) fully disrupted infants' persistent representations. Eight infants (*M* = 8 months, *SD* = 10 days) were presented a computer-based adaptation of the task used in Huntley-Fenner et al. (2002).

Infants were first familiarized with four events. Two events presented one object that appeared at the top edge of a computer screen, either at the left or at the right, descended vertically (7cm/s), and came to rest either on an open stage or behind an occluding screen. In both events the static object (after the lowering of the screen in the latter event) was presented for 10 seconds. In the two remaining familiarization events, two objects appeared simultaneously and descended from the top. In all other aspects, these events were identical to the one-object events.

During the test events, one object appeared from the top, moved downwards, came to rest in full view, and was then hidden by lifting the screen (see Figure 5, A-C). A second object then descended from the top to sit next to the first object behind the occlusion screen (D-F). Each of the described events involved the objects splitting in half midway in their descent, re-approaching one another again, and finally rejoining to form the whole initial object again on the stage floor. Finally, the screen was lowered and a still image was presented for 10 seconds. Infants' looking times at two types of test events were analyzed and compared. In the expected test event both objects appeared upon lowering the screen (T_e), whereas in the unexpected test event the second object had disappeared (T_u).

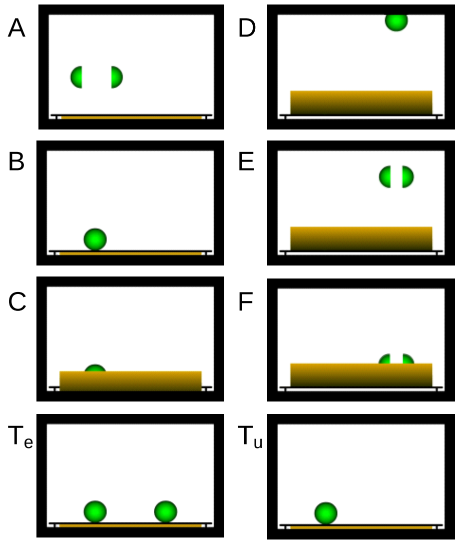


Figure 5. Sample frames in sequence (A to F) from the test trials in Pilot Study A with the expected outcome (T_e) and the unexpected outcome (T_u).

The analyses revealed no difference between looking times at one (*M* = 7.4 s, *SD* = 1.49) or two objects (*M* = 7.4 s, *SD* = 1.25) during familiarization, $t(7) = .15$, $p = .88$. However, infants looked reliably longer at one object (i.e., unexpected event, *M* = 7.6 s, *SD* = 1.11) than at two objects (i.e., expected event, *M* = 6.6 s, *SD* = 1.78) during the test trials, $t(7) = 2.70$, $p = .02$. Nonparametric analysis confirmed the preference for the unexpected event. All infants looked longer at the unexpected than at the expected event, Wilcoxon z = 2.52, $p = .01$.

This finding shows that infants successfully represented the continued existence of an object under conditions of a simple cohesion violation. This supports the weaker explanation of previously demonstrated failures outlined above (Cheries et al., 2008).

2.2 Pilot Study B

The findings of Pilot Study A indicated that cohesion violation does not absolutely interfere with infants' ability to represent the continued existence of an entity. Pilot Study B therefore examined the proposed significance of the number of fragments resulting from a cohesion violation. An action-based task was conducted with 32 infants (mean age = 12 months 9 days, *SD* = 6 days), in which they had to choose one of two cups. Infants were randomly assigned to a condition with a cohesion violation resulting in four fragments (i.e., large collection) and a cohesion violation resulting in three fragments (i.e., small collection). In both conditions infants had to chose between an empty cup and a cup containing the fragments.

The infants sat on their parents' lap opposite the experimenter at a table. At the beginning of the task, the two empty cups were presented to the infants and the experimenter placed the two cups side by side on the table. Next, two trials were presented in a random order, counterbalanced across the infants. In the case using a full cup the experimenter presented an object that was either built of three or four identical Lego bricks. The object was held over the cup, one brick after the other was removed, shown to the infant and placed inside the cup. In the three-fragment condition the experimenter imitated the same motion for an imaginary fourth brick in order to equalize the presentation of the two conditions. To account for the possibility that the infants would reach for the full cup merely based on the attention the experimenter paid to it, the motion for the four bricks was imitated for the second, empty cup.

In the three-fragment condition a significant proportion of children reached for the full cup (13/16), Binomial, p = .02. By contrast, the proportion of infants who chose the full cup in the four-fragment condition did not exceed chance level (10/16), Binomial, p = .45. The two conditions differed significantly, p = .03, two-tailed Fisher's exact test.

These result indicate that the number of fragments plays a critical role in cohesion violations and may relate to the representation of small and large collections (Feigenson & Carey, 2005). The random choice in the case of four fragments corresponds to the previous finding of a loss of representation in the case of a large number of fragments (Chiang & Wynn, 2000). However, there are at least two possible explanations of infants' success in the three-fragment condition. Infants might have (a) represented the mere existence of a substance, or (b) retained additional information about the hidden bricks. That is, this task may not provide information about the kind of entity (i.e., individual kind or substance kind) infants were representing. This was addressed in the main study.

3. STUDY I[1]

3.1 Abstract

Two experiments tested the ability of 8-month-old infants to keep track of entities that do not move according to the rigidity principle (i.e., failure to move with stable boundaries) or the cohesion principle (i.e., failure to move as a connected whole). We found that violations of these principles interfered with the infants' tracking process only in those cases where the motion patterns of an entity resulted in (a) ambiguity about the specific location to be tracked in space and time, and (b) ambiguity about the kind of entity to be tracked.

3.2 Introduction

The visual input is not segregated into distinct units. Nevertheless, the basic units of a wide range of infants' perceptual and cognitive processing (such as physical reasoning, categorizing, or enumerating) are individual objects (e.g., Carey & Xu, 2001; Leslie et al., 1998; Scholl, 2007; Scholl & Leslie, 1999; Spelke, Vishton, & von Hofsten, 1995). A fundamental question is, what kind of visual features are processed and tracked through space and time as individuated entities? Recent research suggests that individual-based processing is brought to bear not only with *solid regions of matter* (i.e., objects as defined by Spelke) (e.g., Spelke et al., 1992), but may also be applied when tracking collective entities (e.g., a flock of birds) and non-rigid substance (e.g., a cloud) (Chiang & Wynn, 2000; Huntley-Fenner et al., 2002;

[1] A similar version of this chapter is submitted for publication as: Schaub, S., Bertin, E., & Cacchione, T. Infants' tracking of non-rigid and non-cohesive entities.

vanMarle & Scholl, 2003; Wynn et al., 2002). However, this process is not applicable to the pouring motion of a non-solid substance (Huntley-Fenner et al., 2002; Rosenberg & Carey, 2006; vanMarle & Scholl, 2003).

Non-solid substances present the ontological opposite of solid, bounded objects, and do not obey the physical laws that constrain object motion. Water or sand, for instance, constantly change their shape and spread while moving. That is, solid objects and non-solid substances differ in terms of *rigidity* (i.e., failure to preserve a constant shape) and *cohesiveness* (i.e., failure to preserve internal connectedness). Due to these characteristics, non-solid substances provide no criteria for individuation. That is, they are not separable either on the basis of spatiotemporal criteria (e.g., internal coherence) or featural criteria (e.g., stable shape), unless a non-intrinsic criterion is added (e.g., a *pile* of sand, a sand*castle*). This is reflected in numerous natural languages in the labeling of substances using mass nouns (i.e., as opposed to count nouns such as *a castle* or *a glass* for the labeling of bounded objects). Mass nouns can only be indirectly individuated by portioning them, as in a *glass* of water or a number of *piles* of sand (e.g., Gordon, 1985; Imai & Gentner, 1997; Prasada et al., 2002; Soja et al., 1991; Subrahmanyam et al., 1999).

Recent research has highlighted the contrast between individuated objects and non-individuated substances by demonstrating adults' and infants' difficulties in keeping track of individuated portions of non-solid substances (see Cheries et al., 2009; Rosenberg & Carey, 2009, for reviews). Adults failed to track discrete portions of a non-solid substance in a multiple-object tracking task when a characteristic pouring motion was performed (vanMarle & Scholl, 2003). Similarly, 8-month-old infants failed to build individuated representations of two sand piles, even when they were poured behind two distinctly separate occluding screens (Huntley-Fenner et al., 2002; see also Rosenberg & Carey, 2006).

However, infants' ability to establish individuated representations, and adults' object-based attention do not solely apply to the counterpart of non-solid substances (i.e., solid, bounded objects) either. For instance, infants were able to represent two portions of a non-rigid substance (i.e., a molding compound) that were lowered behind two differently located occlusion screens (Huntley-Fenner et al., 2002). Similarly, adults' attentive tracking of non-rigidly moving entities (i.e., transforming polygon figures) was as accurate as their tracking of rigid objects (i.e., stable rectangles) (vanMarle & Scholl, 2003). Equally, infants were able to represent loose assemblies of multiple identical objects as individuated collections if the objects performed a collective motion (Wynn et al., 2002). The same has been found in adults' attentive tracking of collective entities (i.e., groups of four rectangles), it being as accurate as the tracking of rigid objects (vanMarle & Scholl, 2003).

While infants were able to build and track individuated representations of non-cohesive collections, they failed to do so with a solid object that was divided up into a non-cohesive collection (Cheries et al., 2008; Chiang & Wynn, 2000). Chiang and Wynn presented 8-month-old infants with an object that was hidden behind an occluding screen. Next, a similar object was presented alongside a second screen. However, before hiding this second object, the infants watched the experimenter break it down into its five identical parts (in this case Lego bricks). That is, the experimenter removed each part, lined them up, and only then hid each of them behind the second screen. In the subsequent test phase, infants' visual attention towards the event's expected outcome (object and parts behind their respective screens) and the unexpected outcome (no parts behind the second screen) did not differ from each other. Even the simplest cohesion violation—the breaking of an object in half—affected infants' representational abilities. In Cheries et al. (2008), 12-month-old infants failed to choose the larger of two hidden crackers when it was broken into two pieces before being placed in a cup. However, instead of simply requiring the infants to represent *something* behind one screen and *something* behind a second screen (Chiang & Wynn, 2000; Huntley-Fenner et al., 2002), the infants in Cheries et al. had to additionally compare the sizes of the hidden crackers. That is, apart from remembering that something was hidden in each cup, the infants needed to maintain representations of the features of the crackers (i.e., small vs. large). Adult research found that an identical type of cohesion violation (i.e., splitting in half) did not fully disrupt the adults' object-tracking mechanism. That is, Mitroff, Scholl, and Wynn (2004) demonstrated that an object representation established for a discrete object (i.e., object file, see Kahneman et al., 1992) persists the splitting of the object in halves. However, the splitting did not remain without consequences, severely limiting the observers' ability to maintain information about the original object. Overall, previous research has shown that object tracking operates optimally with solid objects. However, this does not mean that object tracking is restricted to solid objects.

The failures and successes in building individual-based representations described above do not appear to occur at random. Chiang and Wynn (2000) have formulated two propositions that may explain this pattern (see also vanMarle & Scholl, 2003). The first addresses the difficulty that *changes in the observers' representations from object kind to substance kind* impose on the tracking process (i.e., entity kind explanation). The second account addresses the *spatiotemporal ambiguity* associated with non-cohesively and non-rigidly moving entities (i.e., spatiotemporal ambiguity explanation).

3.2.1 Change from Object Kind to Substance Kind

One of the explanations by Chiang and Wynn (2000) for previous failures in infants' object tracking through cohesion violation related to representations of the entity kind. That is, the decomposition of the pile-like object entails a transformation from an entity belonging to an *object kind* (i.e., pile) to an entity belonging to *substance kind* (i.e., collection). Each of these entities is associated with a distinctive spatiotemporal motion pattern, meaning that, as outlined above, the core principles constraining the motion of object kinds but not substance kinds. As a result, the transformation of an object into a substance produces ambiguity about the kind of entity being tracked.

Two predictions can be extrapolated from this explanation. First, the observer will have difficulty maintaining a persistent representation if a rigid object transforms into a non-rigid substance. This prediction is supported by a number of studies that have demonstrated that infants perceive rigidity and non-rigidity as belonging to two different entity kinds (Gibson et al., 1978; Gibson et al., 1979; Walker et al., 1980). For example, infants regard the rigidity of an object's shape during motion as constituting an invariant property of the object, and dishabituate to a deforming motion if they were initially habituated to different types of rigid motion, and vice versa. Second, there will be differing results in the case of cohesion violations for transformations resulting in small or large numbers of fragments, because only large numbers lead to a change in the entity kind (object kind to substance kind). To explain why this is so, we have to consider infants' representations of small and large numbers. The evidence converges to support the assumption that infants possess two separate and distinct systems by which they represent numbers. One system represents the individual objects in small sets containing up to three objects (Antell & Keating, 1983; Feigenson, Carey, & Hauser, 2002; Feigenson, Carey, & Spelke, 2002; Koechlin, Dehaene, & Mehler, 1997; Simon, Hespos, & Rochat, 1995; Starkey & Cooper, 1980; Strauss & Curtis, 1981; Uller, Carey, Huntley-Fenner, & Klatt, 1999; Wynn, 1992; but see Clearfield & Mix, 1999; Wakeley, Rivera, & Langer, 2000). The second system represents a continuous measure of the approximate amount of larger sets (Brannon, 2002; Xu, 2003; Xu & Arriaga, 2007; Xu & Spelke, 2000; Xu et al., 2005; but see McCrink & Wynn, 2004). Recent findings demonstrate a dramatic breakdown in infants' representational abilities when the given set size limit of the small-number system is exceeded (Barner, Thalwitz, Wood, Yang, & Carey, 2007; Feigenson & Carey, 2003, 2005; Feigenson, Carey, & Hauser, 2002). For example, in Feigenson and Carey (2005) infants preferred three crackers over two crackers (and two over one), but failed to choose the larger over the smaller amount when they differed by a ratio of 4:1. However, infants succeeded in a 4:0 ratio, which suggests that they maintained the representation of *something* (i.e., cracker substance) inside the cup. Given these results, it seems reasonable to assume that the representation of small sets is object-based, while the representation of large sets is substance-based. Thus, while fragmentation into a small number remains within object-based representation, fragmentation into a large number is beyond the processing abilities of this system. Consequently, only the latter transformation involves a change in entity kind (object kind to substance kind), while the former does not (object kind to object kind).

Indeed, failures in infants' tracking of fragments after cohesion violations reported in previous research attests to a differing impact depending on the number of resulting fragments. A closer examination of these failures suggests that cohesion violation per se may *affect* the content of infants' representation, but does not necessarily *disrupt* the tracking process completely (Cheries et al., 2008). The only proven disruption of the tracking process occurs when cohesion violations result in a number of fragments exceeding the set size limit. For example, infants were unable to keep track of a non-cohesive entity when they were faced with a major cohesion violation producing five fragments, the number being above the set size limit of three items (Chiang & Wynn, 2000). However, in cases where the violation resulted in a number of fragments below the set size limit (i.e., two fragments in Cheries et al., 2008), there is no objective evidence that infants failed to further represent the fragmented entity inside the cup. That is, infants may still have represented at least *something* in each of the two cups, but may have simply failed to represent the features of the hidden entity (i.e., *what* the thing was).

3.2.2 Spatiotemporal Ambiguity

If solid objects and non-solid substances are placed in a continuum calibrated by varying degrees of rigidity and cohesiveness, solid objects (which optimally enable tracking) would appear at one extreme, and non-solid substances (which least enable tracking) at the other. However, in between these two opposites are any numbers of other entities that vary in both the degree of their rigidity and their cohesiveness, and, which, consequently, vary in the amount of spatiotemporal ambiguity they exert upon the visual system.

In the study by vanMarle and Scholl (2003) adults' attentive tracking was disrupted neither by non-rigid nor by non-cohesive motion, but rather by the substance-characteristic motion of dynamic expansion and contraction. Here, participants failed to keep track of individuated entities. Thus, rather than non-rigidity or non-cohesiveness being responsible for the disruption of the adults' tracking process, the authors postulate that it was due to an inability to fixate on a distinct location in space and time. This proposal links back to the example outlined above in the observation of a cloud or a flock of birds. Both entities (i.e., the non-rigid cloud and the non-cohesive flock of birds) enable the viewer to keep track of a single location in space and time. However, if the cloud disintegrates or the flock of birds breaks apart and the birds stop performing a common motion, the representations of individuated entities cannot be upheld and maintained. Like a cloud, the non-rigid substance in Huntley-Fenner et al. (2002) moved as one whole and retained its external boundaries despite changes in shape. Similarly, the multiple dots in Wynn et al. (2002) performed a collective motion identical to that of a flock of birds. Infants' success in these studies therefore may be based on the tracking of single locations. By contrast, failures in infants' tracking of individuated portions described in the literature may be caused by an inability to fixate on a single location in space and time. For example, once the single pile-like object in Chiang and Wynn (2000) was dismantled into its constituent pieces, the initial (single) location in space and time ceased to exist for the observer and new space-time allocations needed to be made to the resulting multiple fragments. Moreover, the innumerable number of independently moving grains of sand constituting the non-cohesive substance in Huntley-Fenner et al. (2002) may have prevented infants from tracking a single spatiotemporal location altogether.

3.2.3 The Current Study

In the present study, we conducted two experiments designed to explicitly examine the theoretical and empirical underpinnings of the explanations provided in the literature to date for the *entity kind* and *spatiotemporal ambiguity*, and as outlined above. A modified version of the habituation procedure used in Wynn et al. (2002) was employed to test the limitations in individual-based tracking in 8-month-old infants. Experiment 1 compared infants' tracking of an entity that was non-rigid throughout the event (substance condition) with the tracking of an initially rigid entity, which lost its rigid boundaries while moving (object/substance condition). According to the spatiotemporal ambiguity explanation both conditions should be successfully represented because they allow the tracking of one particular location in space and time. The entity kind explanation, however, would predict a failure in the object/substance condition given that this event entails a transformation from object kind to substance kind.

Experiment 2 examined infants' tracking of non-cohesive entities. Similarly to Experiment 1, one of the entities was non-cohesive throughout the event (collection condition). In addition, infants were presented with two events of an initially discrete object, which lost its cohesiveness only in the course of motion. One event compared the impact of a cohesion violation within infants' set size limit (object/small collection), while the cohesion violation of the second event exceeded this system (object/large collection). The spatiotemporal ambiguity explanation would predict success in the collection condition because the collective motion provides the opportunity to track one location in space and time, and failure in the case of object/collection conditions because the initial single location in space and time has to be abandoned. However, the entity kind explanation provides different predictions about transformation into a small or a large collection because only the latter entails a transformation from object kind to substance kind.

3.3 Experiment 1

Eight-month old infants were habituated to one or two non-rigidly moving entities. In the substance condition the entity moved with non-rigidly changing boundaries throughout the full event, whereas in the object/substance condition the entity was initially introduced as a rigid object. To assess, whether infants tracked these kinds of stimuli as individuated entities, reactions towards a change in the number of entities was examined during the following test events.

3.3.1 Method

Participants

The final sample consisted of 48 healthy, full-term 8-month-old infants (25 female; mean age=8;1 [months;days] ranging from 7;18 to 8;16. Infants were randomly assigned to the substance condition and to the object/substance condition. Four additional children had to be excluded due to parental interference (2) and experimenter error (2).

Procedures and Stimuli

Infants sat on their parent's lap approximately 60 cm in front of a 30 inch computer monitor, in a separated, darkened room. To prevent bias, parents were instructed to fixate on their children's back of the head and to refrain from looking at the monitor. We presented computer-animated stimuli created with Flash CS3 Professional (Adobe Systems Inc.).

Substance Condition

Randomly shaped entities gradually appeared from an invisible wall at the left-hand side of the computer screen and moved rightwards. The entities constantly changed their shape while moving and gradually disappeared behind an invisible wall on the right end of the screen. There were two habituation conditions. Half of the infants were habituated to one non-rigid entity (Habituation 1). The other half was habituated to two non-rigid entities (Habituation 2, see Figure 6).

Habituation 1 consisted of one entity. During motion, the habituation entity gradually changed its shape into a novel random shape after 1.5 s, 2.5 s, 3.5 s, and in the final position at 4.5 s, behind the invisible wall. After the entity had fully disappeared, a blank screen was shown for 1.5 s before the next loop began. Habituation 2 was similar, except that two random shapes appeared simultaneously on the left side of the screen, 6.7 cm (subtending 6.4° visual angle) apart from one another. One of these motions was similar to the habituation entity of Habituation 1.

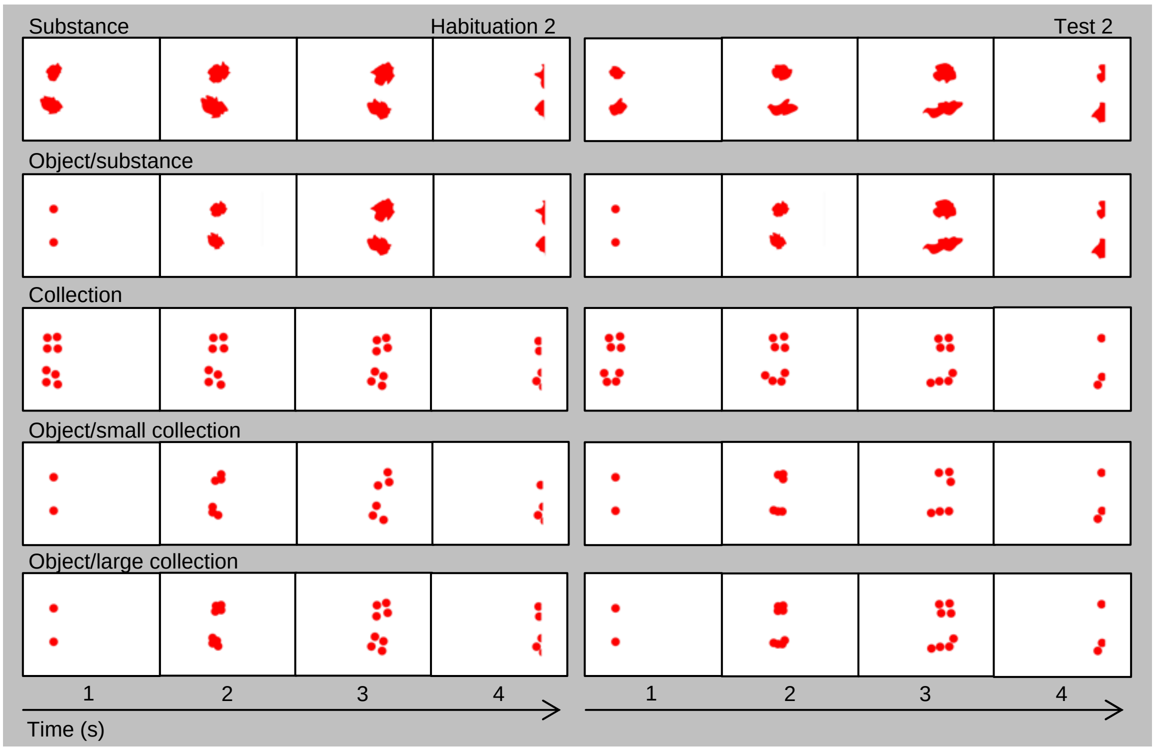


Figure 6. Sample frames in sequence from the habituation and test events from each of the five conditions. The total duration of each event was 4.5 seconds. The timeline corresponds to the appearance of the respective frame. Habituation 1 and Test 1 corresponded to the lower group, in all events, and moved at the vertical middle.

After habituation all infants watched two types of test events in alternation. Test 1 depicted a novel motion of one non-rigid entity. Test 2 depicted novel motions of two non-rigid entities. Apart from the novel shapes, Test 1 was similar to Habituation 1 and Test 2 was similar to Habituation 2. All of these habituation and test entities varied in sizes over the course of motion. The width was ranging from 3.7 cm to 16.2 cm (3.5°-15.4°) and the height was ranging from 5.4 cm to 12.0 cm (5.2°-11.4°).

Each of the described events was shown in loops, until the infant either looked away for two cumulative seconds, or after 60 seconds had passed. In-between all trials an attention getter was shown until infants looked back at the vertical middle on the left-hand side of the screen. As soon as attention was secured, the experimenter started the next trial. The habituation phase ended either when the infant's mean looking time of three consecutive trials was less than half of her or his mean looking time on the first three habituation trials, or when the infant had completed 15 habituation trials. All infants received three pairs of test events, alternating between Test 1 and Test 2. Half of the infants saw Test 1 first (1/2,1/2,1/2), the other half saw Test 2 first (2/1,2/1,2/1).

A camera was mounted on top of the computer screen. The recordings of infants' gazes were transferred to a monitor, and looking times were coded online. A second observer, naïve to the research question and hypothesis, coded 30 percent of the sessions from videotapes. Inter-rater agreement with the first experimenter was high (r = .99). Thus data from online coding was used in the subsequent statistical analyses.

Object/substance Condition

The object/substance condition was identical to the substance condition except that the entity initially appeared as one red dot measuring 3.3 cm in diameter (3.2°). Analogous to the substance condition, Habituation 1 and Test 1 depicted one dot; Habituation 2 and Test 2 two identical red dots placed 9.9 cm apart from each another (9.4°). The dots moved horizontally for 1.5 s and then gradually changed their shape until they had the same shape like the entities in the substance condition. This state was reached after 2.5 s. The remaining events were identical.

3.3.2 Results

Two infants in the object/substance condition (Habituation 1 group) did not meet the habituation criterion. As the results did not differ when they were excluded we left them in the final sample. A comparison of the number of habituation trials completed in the two experimental conditions showed a marginal significant effect of condition, $F(1, 46) = 3.20$, $p = .08$. Infants in the substance condition completed less habituation trials ($M = 6.63$, $SD = 1.35$) than infants in the object/substance condition ($M = 7.71$, $SD = 2.65$). We compared mean looking times in the first three habituation trials with the last three habituation trials for the two experimental conditions (see Figure 7). The 2 (experimental condition) × 2 (number in habituation) ANOVA showed a main effect of habituation phase only, $F(1, 46) = 207.78$, $p = .000$, $\eta_p^2 = .82$. Mean looking times dropped from 34.6 s over the first three trials to 11.8 s over the last three trials. However, a comparison of the mean looking times during the last three habituation trials showed that these were longer in the object/substance condition (14.0 s) than in the substance condition (9.6 s), $F(1, 46) = 5.90$, $p = .02$.

The main interest of the current study was whether or not infants tracked the habituation entities in terms of individuated entities. Two measures were taken as indicators of successful tracking. First, if infants habituated to the number of habituation entities they should demonstrate enhanced interest towards the novel number during test events compared with habituation trials. Second, they should prefer test trials containing the novel number over test trials containing the familiar number. Overall looking times were longer in the object/substance condition (14.8 s) than in the substance condition (10.8 s), $F(1, 46) = 4.96$, $p = .03$, as well as were overall looking times at Test 2 of the two conditions (16.3 s/11.3 s, respectively), $F(1, 46) = 4.93$, $p = .03$. These differences, together with a decline in looking times over the three pairs of test trials, led to random effects in the analyses of absolute looking times. Therefore, a proportional preference score for each measure was calculated in order to compare the conditions. One dishabituation score was calculated by comparing the proportion of looking time spent on the novel number during the first pair of test trials with the looking time spent on the last habituation trial (i.e., first novel test trial:last habituation trial). One novelty preference score was calculated by comparing the proportional looking time spent on the novel number overall with the looking time spent on the familiar number (i.e., test novel:test familiar). A second novelty score compared the same measures for the first test pair only (i.e., first novel test trial:first familiar test trial). In both experimental conditions infants' dishabituation scores and the novelty preference during the first test pair differed significantly from chance (i.e., .5 = equal looking times at the compared events). The overall novelty preference differed from chance only for infants in the substance condition (see Figure 9).

No differences were found between the two conditions in the three preference scores: dishabituation, $F(1, 46) = .001$, $p = .97$, test overall, $F(1, 46) = 1.87$, $p = .19$, and first test pair, $F(1, 46) = .04$, $p = .85$. However, the overall preference score differed from chance only in the substance condition. We therefore analyzed the two conditions separately.

Substance Condition

In order to analyze whether infants looked longer at the novel number during test events a 2 (number in habituation) × 2 (test event) × 3 (test pair) mixed measures ANOVA analyzing mean looking times during test events was computed. The analysis revealed a main effect of test event, $F(1, 22) = 8.06$, $p = .01$, $\eta_p^2 = .27$, based on a preference for the novel number. Infants in the Habituation 1 group looked longer at Test 2, $t(11) = 1.94$, $p = .08$, and infants in the Habituation 2 group looked longer at Test 1, $t(11) = 2.90$, $p = .02$. Additionally, main effects of test pair, $F(2, 44) = 3.78$, $p = .03$, $\eta_p^2 = .15$, and habituation condition, $F(1, 22) = 6.11$, $p = .02$, $\eta_p^2 = .22$, were revealed. Mean looking times declined from 13.8 s in the first test pair to 9.5 s in the last test pair. The main effect of habituation condition was due to longer looking times of infants in the Habituation 1 group (13.3 s) compared with infants in the Habituation 2 group (8.3 s). A Wilcoxon sign test confirmed the preference for the novel number during test events by showing that 18 infants looked longer at the novel number, $z = 2.71$, $p = .007$.

Object/substance Condition

The 2 (number in habituation) × 2 (test event) × 3 (test pair) ANOVA on mean looking times showed a significant interaction of test event × number in habituation, $F(1, 22) = 4.69$, $p = .04$, $\eta_p^2 = .18$, and a significant three-way interaction of test event × number in habituation × test pair, $F(2, 44) = 5.37$, $p = .008$, $\eta_p^2 = .20$. Infants in the Habituation 1 group looked longer at Test 2, $t(11) = 2.28$, $p = .04$. By contrast, infants in the Habituation 2 group looked equally at the two types of test events, $t(11) = -.57$, $p = .58$. In order to further investigate the effect of test pair we analyzed the first pair of test trials separately. However, these looking times followed the same pattern. Infants in the Habituation 1 group looked longer at Test 2, $t(11) = 3.43$, $p = .006$, whereas infants in the Habituation 2 group looked equally at the two types of test events, $t(11) = -1.30$, $p = .22$. This pattern was also confirmed by non-parametric analyses. Ten infants preferred the novel number in the Habituation 1 group overall, $z = 2.20$, $p = .03$, and in the first test pair, $z = 2.75$, $p = .006$, whereas 6 of the infants in the Habituation 2 group preferred the novel number overall, $z = .47$, $p = .64$, and 5 in the first test pair, $z = -1.18$, $p = .24$.

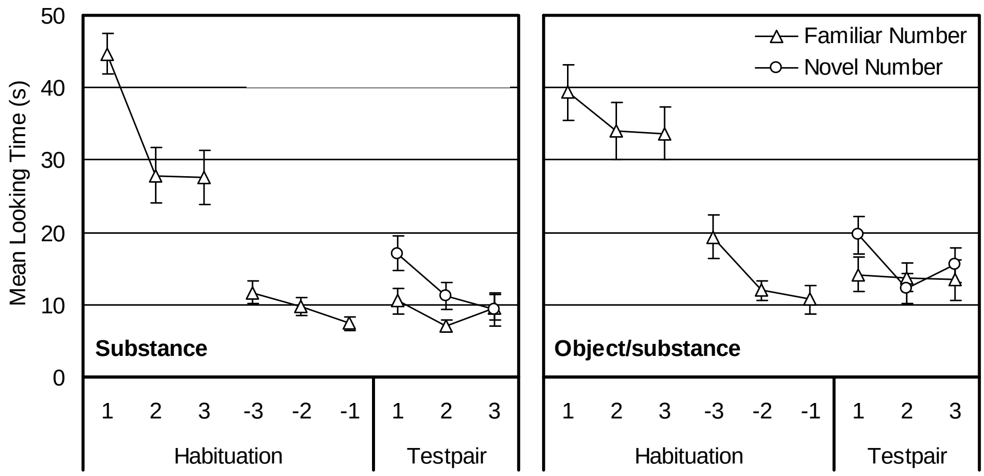


Figure 7. Infants' mean looking times and standard errors at the first three and the last three habituation trials and the two types of test events in Experiment 1.

3.3.3 Discussion

The experiment showed that infants in the substance condition reacted to a change in the number of entities in the analysis of all preference scores. This confirms the findings in the literature that infants are able to track individuated portions of non-rigidly moving entities (Huntley-Fenner et al., 2002). Noticeably, infants in the object/substance condition did not completely fail to notice the change in number.

But while infants in the Habituation 1 group demonstrated a preference for the novel number, infants in the Habituation 2 group looked equally long at both numbers during the test events. We are reluctant to draw any definite conclusions based on these equal looking times, as it would appear likely in this group that the preference for the novel number (Test 1) was masked by a preference to look at a two-item display instead of a one-item display (i.e., to look at more instead of less stuff). A similar preference towards two entities over one entity has been reported in other studies (e.g., Huntley-Fenner et al., 2002).

Nevertheless, additional differences between the substance and the object/substance condition were observed. We found that infants spent more time looking at the events of the object/substance condition both during habituation and during tests. This might indicate that the events in the object/substance condition were more complex than the events in the substance condition. Indeed, longer looking times have been shown to positively correlate to visual complexity (e.g., contour length, number of corners in random shapes) (e.g., R. F. Caron & Caron, 1969; Hunter, Ames, & Koopman, 1983; McCall & Kagan, 1967). Greater visual complexity in the present events may have arisen from the fact that the object/substance condition involved two types of motion (rigid and non-rigid), whereas the substance condition did not. That is, only the initial introduction of the rigid object led to a transformation in entity kind (i.e., from object-kind to substance-kind) (cf. Gibson et al., 1978; Gibson et al., 1979; Walker et al., 1980).

To summarize, neither non-rigidity by itself (substance condition) nor a transformation in entity kind (object/substance condition) fully disrupted infants' tracking process. The low-level of spatiotemporal ambiguity involved in the motion pattern of the entities in both conditions could explain this success. That is, both events provided the infants with the opportunity to keep track of a single stable location of the entity in space and time (e.g., the center of the entities).

3.4 Experiment 2

Experiment 2 examined infants' tracking of collections of objects. In the object/small collection condition infants were presented with a bounded object that split into three fragments (i.e., a number within the set size limit), whereas infants in the object/large collection condition saw a split into four fragments (i.e., a number exceeding the set size limit). In the collection condition the unconnected fragments were introduced as a non-cohesive collection at the beginning of the event. Again, infants were habituated to one or two moving objects/collections and their reactions towards a change in the number of entities were tested.

3.4.1 Method

Participants

The final sample consisted of 72 healthy, full-term 8-month-old infants (35 female; mean age = 8;2, ranging from 7;15 to 8;15. Roughly equal numbers of boys and girls were randomly assigned to the collection condition, object/small collection condition and to the object/large collection condition.

Procedures and Stimuli

Infants were presented with events where either single dots (object/small collection, object/large collection condition) or collections of dots (collection condition) appeared on the left side of the computer monitor (see Figure 6). As in Experiment 1, the entities moved from the left to the right. Overall, the events were analogous to the ones used in Experiment 1. Exceptions will be reported in the descriptions of the different conditions.

Collection Condition

Instead of single dots as in Experiment 1, collections of randomly placed dots appeared at the left-hand side of the computer screen. One group of infants was habituated to one collection (Habituation 1); a second group of infants was habituated to two collections (Habituation 2). By their entering, the two collections were approximately 4.4 cm apart from one another (4.2°).

As before, both habituation groups watched two types of test events. Test 1 presented one collection with a novel arrangement of dots. Test 2 presented two novel collections. Here, the collections were approximately 6.7 cm apart from one another by their entering (6.4 °). Each collection consisted of four identical red dots, each measuring 3.3 cm in diameter (3.2°). The dots moved from the first position (i.e., hidden by the left-sided invisible wall) to a novel position after 1.5 s, 2.5 s, 3.5 s and reached their final position after 4.5 s (i.e., hidden by the right-sided invisible wall). Each dot changed its position independently. However, the single dots never overlapped, and the dots forming a collection performed a common motion. The dots were placed within the contours of the shapes used in the substance condition of

Experiment 1. Thus, the minimal and maximal sizes of the outer contours of the collections corresponded to the measurements of the shapes of Experiment 1. The remaining procedure was identical to Experiment 1.

Object/small Collection Condition

Similar to the object/substance condition of Experiment 1, red dots (number depending on habituation) measuring 3.3 cm (3.2°) in diameter appeared initially on screen. However, the single dot in Habituation 1 and in Test 1 actually consisted of three superposed dots (i.e., only the topmost dot was visible). As such, these dots moved horizontally for 1.5 s. Afterwards the three dots started to move independently and reached three (of the four) positions of dots in the collection condition after 2.5 s, 3.5 s and 4.5 s. Habituation 2 and Test 2 were similar to that except that each of the two appearing dots consisted of three superposed dots (see Figure 6).

Object/large Collection Condition

The events were analogous to the ones of the object/small collection condition except that the visual transformation was from one single dot to four identical dots. Thus after the splitting, the events of the object/large collection condition were identical to the ones of the collection condition.

Thirty percent of the sessions were coded by a second observer. Because the inter-rater agreement with the first experimenter's online codings was high (r = .97), the data from the online coding was used in the subsequent analyses.

3.4.2 Results

One infant of the object/small collection (Habituation 1 group) did not meet the habituation criterion. We left her in the final sample because the results did not change upon exclusion. A comparison of the number of habituation trials completed showed no effect of experimental condition, $F(2, 69) = .42$, $p = .66$. Infants' mean number of habituation trials was 7.71 ($SD = 2.40$) in the collection, 7.58 ($SD = 2.72$) in the object/small collection condition, and 8.25 ($SD = 2.88$) in the object/large collection condition. The comparison of the looking times during the first three habituation trials with the last three trials for the three experimental conditions showed a main effect of habituation phase only, $F(1, 69) = 230.23$, $p = .000$, $\eta_p^2 = .77$. Mean looking times declined from 30.0 s over the first three habituation trials to 10.7 s over the last three trials (see Figure 8).

As in Experiment 1, we calculated three proportional preference scores. One score compared the proportion spent on the first test containing the novel number with the proportion spent on the last habituation trial (first novel test trial:last habituation trial); a second score compared the proportion spent on the novel number during test events with the proportion spent on the familiar number overall (test novel:test familiar), and a third score in the first test pair (first novel test trial:first familiar test trial). We conducted one-way ANOVAs to compare these scores. The three conditions did not differ in the dishabituation score, F(2, 69 = 1.46, p = .24, and in the overall test score, $F(2, 69) = 1.06$, $p = .35$. However, a marginal difference was found within the first test pair, $F(2, 69) = 2.43$, $p = .096$. Pair-wise comparisons of the three conditions showed that this was due to smaller preference scores in the case of the object/large collection condition (see Figure 9). The next sections will highlight these differences by reporting the results for the three conditions separately.

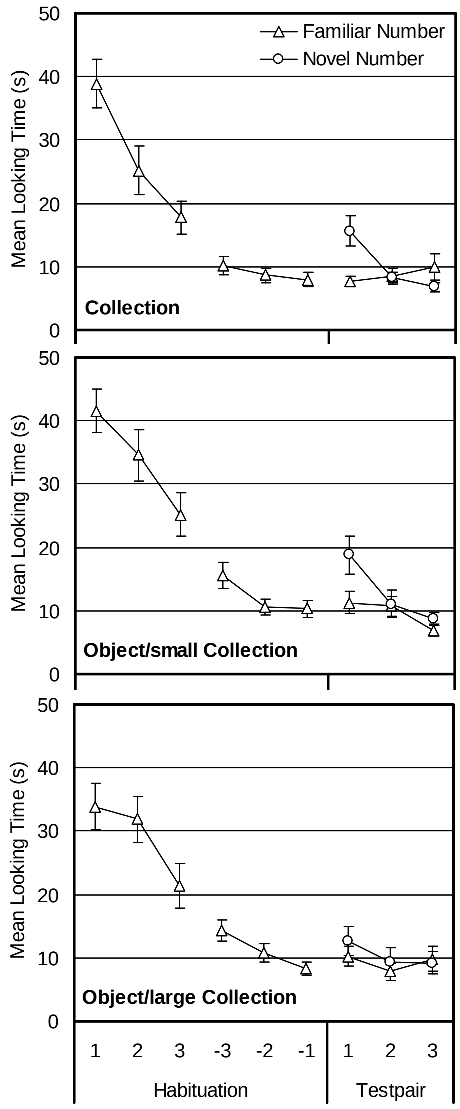


Figure 8. Infants' mean looking times and standard errors at the first three and the last three habituation trials and the two types of test events in Experiment 2.

Collection Condition

As in Experiment 1, a 2 (number in habituation) × 2 (test event) × 3 (test pair) ANOVA on mean looking times was computed in order to analyze the preference for the novel number during test events. The analysis showed a significant interaction of test event × test pair, $F(2, 44) = 9.51$, $p = .000$, $\eta_p^2 = .30$. However, a separate analysis of the first pair of test trials revealed the expected main effect of test event, $F(1, 22) = 12.12$, $p = .002$, $\eta_p^2 = .36$. During the first test pair, infants who were habituated to the one-entity display looked longer at the two-entity test display, $t(11) = 2.99$, $p = .01$, and vice versa, $t(11) = 1.83$, $p = .095$. Also, a significant number of infants (18) preferred the novel number in the first test pair, $z = 2.89$, $p = .004$.

Object/small Collection Condition

The 2 (number in habituation) × 2 (test event) × 3 (test pair) ANOVA on mean looking times during test events showed a main effect of test event, $F(1, 22) = 12.97$, $p = .002$, $\eta_p^2 = .37$. Infants in the Habituation 1 group preferred Test 2, $t(11) = 3.09$, $p = .01$, and infants in the Habituation 2 group preferred Test 1, $t(11) = 2.35$, $p = .04$. Additionally, overall looking times declined over the three test pairs from 12.2 s in the first to 11.4 s in the last test pair, as expressed by a main effect of test pair in the overall ANOVA, $F(2, 44) = 6.75$, $p = .003$, $\eta_p^2 = .24$. Twenty-one infants looked longer at the novel number overall, $z = 3.20$, $p = .001$, and 18 in the first test pair, $z = 2.89$, $p = .004$.

Object/large Collection Condition

The 2 (number in habituation) × 2 (test event) × 3 (test pair) ANOVA revealed a main effect of habituation condition only, $F(1, 22) = 6.04$, $p = .02$, $\eta_p^2 = .22$. Mean looking times of infants in the Habituation 1 group were longer (12.6 s) than of infants in the Habituation 2 group (7.0 s). Neither the Habituation 1 group, $t(11) = .57$, *p* = .58, nor the Habituation 2 group, *t*(11) = 1.17, *p* = .27, looked longer at the display with the novel number during test events. Also, only half of the infants looked longer at the novel number overall, *z* = .63, *p* = .53, and 11 in the first test pair, *z* = -.63, *p* = .53.

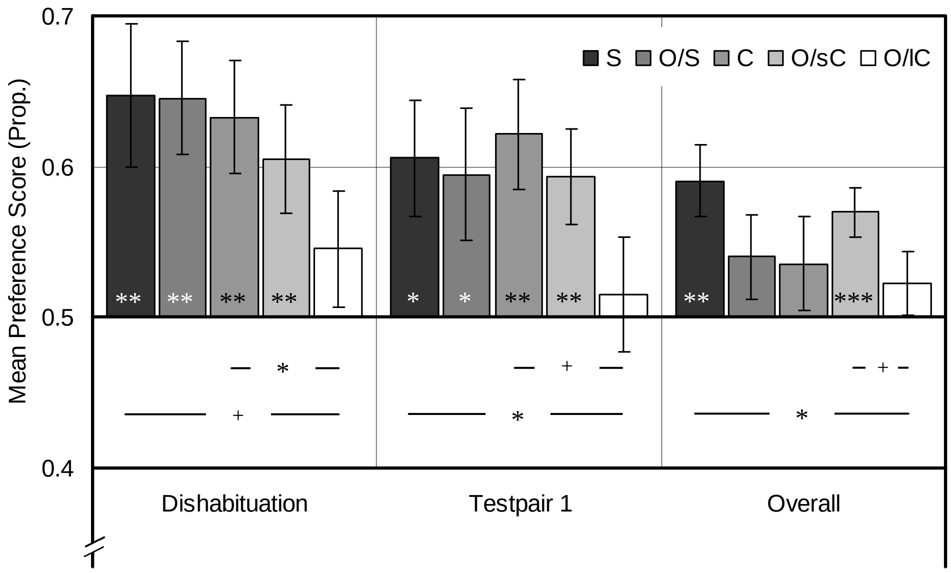


Figure 9. Proportional scores indicating a preference for the novel number when comparing the novel number during the first test trial with last habituation trial (dishabituation), the novel number with the familiar number in the first test pair (Testpair 1) and overall for the substance (S) and the object/substance (O/S) condition of Experiment 1, and the collection (C), the object/small collection (O/sC), and the object/large collection condition (O/lC) of Experiment 2.

3.4.3 Discussion

Infants noticed the novel number of moving collections. This suggests that they were able to track collections as discrete entities. This is in line with the findings in the literature indicating that infants (as well as adults) are able to represent multiple objects that undergo collective motion (e.g., a flock of birds) as individuated collections (Bloom & Veres, 1999; Braddick, 1980; vanMarle & Scholl, 2003; Wynn et al., 2002). By contrast, infants failed to track entities that were initially introduced as rigid entities, and only subsequently underwent a cohesion violation in the course of motion. However, this failure was found only in the case of a split into four pieces. If the split resulted in only three pieces, infants successfully tracked the remaining fragments as a collection.

The negative impact on the infants' tracking process in the case of four fragments confirms previous findings (Cheries et al., 2008; Chiang & Wynn, 2000; Huntley-Fenner et al., 2002). However, it is important to reiterate that in contrast to these findings, a split into three fragments in the above experiment did not affect the tracking process. There is a possibility that, compared to other studies, methodologically our events may have facilitated the tracking process. First, in contrast to previous studies we employed an infant-controlled habituation paradigm guaranteeing that each infant had ample opportunity to fully encode the entities. Second, as opposed to previous studies, our events did not involve prolonged occlusion (Chiang & Wynn, 2000; Huntley-Fenner et al., 2002) or containment (Cheries et al., 2008), both of which are conceptually demanding for infants (e.g., Bogartz, Shinskey, & Schilling, 2000; Munakata, McClelland, Johnson, & Siegler, 1997). By contrast, in our events the entities simply moved off and back on the display again, thus disappearing only briefly. Taken together, these methodological alterations may have contributed to the infants' successful tracking, even in the case of cohesion violation. However, these methodological alterations applied to all the events in the current experiment, meaning that they cannot explain infants' tracking failure in the case of a split into four fragments.

The success in the case of a split into three, however, conforms to adults' object tracking, which has been shown to outlast a cohesion violation resulting in a small number of fragments (Mitroff et al., 2004). Furthermore, the contrasting results of three vs. four fragments mirror the other reports of infants successfully representing sets of up to three items, and their failure in representing sets containing four items (e.g., Barner et al., 2007; Feigenson & Carey, 2003, 2005; Feigenson, Carey, & Hauser, 2002). That is, even if three fragments and four fragments differ to each other by only a single dot, these two numbers *are* actually fundamentally different in that they belong to two distinct representational systems (see Cordes & Brannon, 2008; Feigenson et al., 2004, for reviews). Consequently, a transformation in entity kind occurred only in the case of a split into four (i.e., substance-based representation), but not in the case of a split into three (i.e., object-based representation). Note that in events where two entities were fragmented, the overall number of resulting dots appears to exceed infants' set size limit (i.e., six or eight dots). However, previous research has shown that infants can compare at least two sets, each of which contains up to three items (i.e., parallel individuation, see Feigenson & Carey, 2005). We can therefore conclude that the infants in the present study referred to the number of *individuated clusters* as being novel, and not to the overall number of single dots.

To summarize, the cohesion violations presented in Experiment 2 did not have an all-or-nothing impact on infants' tracking behavior. Rather, they appear to affect tracking to varying degrees according to the amount of non-cohesiveness they produce (i.e., spatial ambivalence). This confirms recent findings in non-human primates (Cacchione & Call, 2009). Moreover, the impact was discernible only if infants witnessed a transformation from object kind to substance kind, but not when the transformation remained object kind.

3.5 General Discussion

Three main conclusions can be drawn from our results: (a) violations of rigidity have less influence on infants' tracking than violations of cohesiveness; (b) cohesion violations have no absolute impact on infants' tracking, but the influence varies by degree in accordance with the level of cohesion violation; and (c) the representation of entity kind is dictated by the spatiotemporal properties of a moving entity.

Infants were able to track entities that moved with non-rigidly changing boundaries. Even in the case of a transformation in entity kind (rigid object/non-rigid substance) infants' tracking was not fully disrupted. As indicated in the discussion section of Experiment 1, it appears possible that infants in all test conditions noticed the change in the number of entities, but that this preference was sometimes masked by a greater preference to look at two dots rather than one. By contrast, infants failed to track an object splitting into multiple fragments if the number of resulting fragments exceeded the signature limit of three items. This is in line with the many observations on the impact of cohesion violations on infants' object processing (Huntley-Fenner et al., 2002; Cheries et al., 2008; Chiang & Wynn, 2000). Cohesion violations produce a higher degree of spatial ambivalence than rigidity violations. When an object splits into multiple parts, the visual system is obliged to abandon the single location that was attended to initially, and to scatter attention amongst the plurality of novel locations. In the case of the non-rigid movement, the initial location in space and time need not be abandoned. In this case, successful tracking was possible as long as the infant managed to trace any one surface point through space and time (cf. vanMarle & Scholl, 2003).

Despite the spatial ambivalence produced by cohesion violations outlined above, we found that these violations did not disrupt the tracking process under all circumstances. First, and in line with previous findings, we found that infants were able to track non-cohesive collections on the basis of the individual collection (Wynn et al., 2002). Second, and surprisingly, we found that a split into three fragments did not disrupt infants' tracking process, thus suggesting that infants were able to maintain the representation despite the vanishing of the initial location in space and time. This success contrasts with previous findings and with the proposition that the cohesion violation itself disrupts the process (Cheries et al., 2008; Chiang & Wynn, 2000).

First of all, however, the contrasting results could conceivably be due to the kind of entity the resulting fragments constitute. That is, while the transformation into three fragments remains within object kinds, a transformation into four objects involves a change from object kind to substance kind. Nevertheless, it is important to remember that the transformation in entity kind did not fully disrupt the tracking process in the case of non-rigid entities. The transformation from an object kind to a substance kind can thus not be the sole cause of the failure in the case of a split into four.

It needs to be noted at this juncture that there is potentially another perspective from which the difference between the representations of three vs. four fragments can be considered, namely other than merely referring to the kinds of entities they constitute. From this perspective the resulting number of fragments themselves vary greatly in their spatiotemporal parameters. While three objects constitute a set of multiple, spatiotemporally well-defined individual items, four objects constitute an ambiguous set that does *not* consist of spatiotemporally defined individual items. Consequently, while it is possible to attend to a novel object after splitting when the transformation involves a split from one to three objects, this is no longer possible in a split resulting in a collection because the collection does not provide single objects that can be attended to. It should be added that there is a potential relevance in the fact that this line of argument is mirrored in the findings of Mitroff et al. (2004), who established that in adults' attentive object tracking the object representation outlasts a split into two—in other words that adults' tracking process actually performed novel space-time allocations to the two resulting objects.

To summarize, the results attained in the experiments highlight the fact that the spatial ambivalence generated by the presented events plays a decisive role. Importantly, the results cannot be fully explained by the entity kind explanation, because a transformation in entity kind failed to disrupt infants' tracking in the case of non-rigid entities (i.e., entities with stable locations in space and time). In the case of cohesion violation, however, it was established that the degree of spatial ambivalence was directly linked to entity kind. That is, novel space-time allocations were performed within object-to-objects transformations (i.e., a split into three), but not within object-to-substance transformations (i.e., a split into four). These findings therefore indicate that the possibility to track a visual array either as an individuated or as a non-individuated entity may actually be *defined* by spatiotemporal properties.

There are two aspects that support this proposition. First, visual arrays that provided specific locations in space and time were tracked as individuated entities (i.e., non-rigid substance, collection). Second, visual transformations caused by a cohesion violation did not affect the tracking process when the transformations were retained within the system representing individual objects. In this case, the observer has to abandon the initial representation of the object, but can reassign her or his representation to novel instances of individual objects (i.e., multiple distinct locations in space and time). By contrast, if the transformation results in a number of fragments that exceeds object-based representation, the prior constructed object representation cannot be reassigned to the novel instances of individual objects (i.e., a single ambiguous location in space and time).

It is necessary to emphasize that this evidence is indicative, but not conclusive, and that a definitive clarification of the interconnections postulated here would require considerably more experimental work than it was possible to undertake within the framework of our single investigation. However, and despite their open-ended nature, the findings of this particular study open up lines of inquiry that are of intrinsic scientific significance. First, Cheries et al. (2008) have provided two potential explanations for the failure to choose the larger cracker when split in two, and our results would tend to confirm that infants maintain a representation of "cracker-stuff", but not of the size of the cracker. A conclusive test of this claim would be to omit the size information, and to give the infants the choice between a broken cracker and an empty cup (cf. Feigenson & Carey, 2005). Second, additional research is required to address the proposed relationship between infants' object processing under conditions of cohesion violations and infants' numerical object processing. In our experiment, for instance, the findings could potentially be explained by infants' chunking abilities (i.e., the binding of multiple objects into a single set). Feigenson and Halberda (2004; 2008) demonstrated that infants were able to build chunks out of a small number of objects (i.e., two), meaning that future research needs to address whether chunking—as Feigenson and Halberda (2008) have hypothesized and as the current study would indicate—is limited to three objects per chunk. Third, the initial conclusion arrived at here that spatiotemporal ambiguity plays a decisive role in infants' object tracking potentially supports the claim formulated by numerous scholars that failures in infants' non-object tracking may be due to the identical object-tracking mechanisms governing adults' object-based attention (e.g., Carey & Xu, 2001; Cheries et al., 2009; Chiang & Wynn, 2000; Feigenson & Carey, 2003; Huntley-Fenner et al., 2002; Scholl & Leslie, 1999). Once again, the issue requires further research. For example, similar to infants, adults are limited in the number of objects they can attend to in parallel (e.g., Pylyshyn & Storm, 1988). However, while previous research has shown that object representations outlast simple violations of the cohesion principle (Mitroff et al., 2004), none of the work to date has addressed the question whether the number of fragments is critical in adults' object tracking under cohesion violation conditions.

4. STUDY II[2]

4.1 Abstract

There is compelling evidence for parallels between infants' and adults' tracking of multiple moving objects. However, these findings are based on different experimental paradigms. To accommodate for this, the current study presented 10-month-old infants (*n* = 59) and adults (*n* = 21) with the same computer animated events where different numbers of dots (1 to 6) simultaneously moved across a screen. Before reaching their final position a single dot was secretly added to each of these events (experimental condition). Direction and duration of gazes towards the additional dot were measured by the means of an eye-tracking device, and compared to events, where the additional dot was present throughout the full event (control condition). The experimental group allocated more attention to the appearing dot compared with the control group, except in the case of 5 dots. This suggests that (a) both age groups detected a dot that was added to a small number (1 to 4), and (b) both age groups may succeed to track a larger number (6) if the single dots are grouped.

4.2 Introduction

The processing of numerosities has engaged scholars from the beginnings of experimental psychology. "Consciousness will thus be at its maximum of intensity when attention is concentrated on a single object; and the question comes to be, how

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[2] A similar version of this chapter is submitted for publication as: Schaub, S., Bertin, E., & Cacchione, T. Parallels in infants' and adults' tracking of multiple moving objects.

many several objects can the mind simultaneously survey, not with vivacity, but without absolute confusion?” (Sir Hamilton, 1877, p. 254). When reading this quote, one may especially think of a young infant, whose attention is entirely directed towards a single object, appearing to have forgotten the objects she or he examined moments ago. However, ample research now clearly demonstrated infants’ ability to represent the continued existence of even multiple objects (see Cordes & Brannon, 2008; Feigenson et al., 2004, for reviews). Even more, these findings largely parallel the findings of adults’ attention towards multiple objects (e.g., Pylyshyn & Storm, 1988). However, the assumption of a common mechanism that keeps track of multiple objects in infants and adults is based on findings from different experimental paradigms, and thus indirect at best (Carey & Xu, 2001). The goal of the present study is to directly compare infants’ and adults’ ability to monitor multiple objects using the same experimental setup.

The classic paradigm to study the simultaneous monitoring of multiple objects in adults was introduced by Pylyshyn and Storm (1988). In this multiple-object tracking task, several identical objects are randomly located on a screen. A subset of these objects is identified as target stimuli, which need to be tracked when all stimuli start to move. Finally, adults are asked to identify the target stimuli once all stimuli have stopped moving. Converging evidence shows that adults are able to simultaneously keep track of about four objects (Bahrami, 2003; Cavanagh & Alvarez, 2005; Culham et al., 1998; Scholl & Pylyshyn, 1999; Sears & Pylyshyn, 2000; Yantis, 1992). A similar upper limit has been observed in adults’ subitizing (i.e., the instant recognition of the numerosity in a set). That is, up to about four items are enumerated accurately and without effort, whereas the enumeration of more items is effortful and error prone (e.g., Jensen, Reese, & Reese, 1950; Kaufman, Lord, Reese, & Volkmann, 1949; Mandler & Shebo, 1982; Saltzman & Garner, 1948; Trick & Pylyshyn, 1994).

The limitations in object tracking and subitzing were explained by the fact that two distinct processes act on small and large sets (e.g., Revkin, Piazza, Izard, Cohen, & Dehaene, 2008; Sathian et al., 1999). According to this account, small sets of objects need not to be enumerated. Rather, the objects in a set are accessed in parallel by a process involving object-based visual attention. During this process, *indexes* are allocated to discrete objects in the visual field. These remain attached to the selected objects while they move through space and become themselves available for higher level cognitive processes (e.g., object files, Kahneman et al., 1992; or FINSTs, Pylyshyn & Storm, 1988; Sears & Pylyshyn, 2000). However, this system is limited to small sets. If the number of objects exceeds the four-item limit, one is forced to serially count (if an exact number is asked) or approximate the number of objects (approximate number system, ANS) (see Feigenson et al., 2004; Libertus & Brannon, 2009, for reviews).

In infancy, converging evidence demonstrates the ability to simultaneously attend to about three objects. Looking time studies have shown that newborn infants dishabituate to static (Antell & Keating, 1983; see also Clearfield & Mix, 1999; Feigenson, 2005; Feigenson, Carey, & Spelke, 2002; Starkey & Cooper, 1980; Starkey, Spelke, & Gelman, 1990; Strauss & Curtis, 1981) and 8-month-old infants to dynamic displays (Van Loosbroek & Smitsman, 1990) of sets containing one object less (or one object more) than the sets in the habituation displays. Also, 5-month-old infants anticipate the outcome of addition and subtraction events where an object is either added to or removed from previously hidden objects. This has been shown in looking-time studies employing the violation of expectation paradigm (Wynn, 1992; see also Kobayashi, Hiraki, Mugitani, & Hasegawa, 2004; Koechlin et al., 1997; Leslie & Chen, 2007; Simon et al., 1995; Uller et al., 1999; Wakeley et al., 2000). Similarly, action-based tasks have shown that by 12 months, infants search for precisely three objects, which they have observed being hidden in a box (Feigenson & Carey, 2003, 2005). Moreover, they consistently choose the larger of two quantities of crackers, which are placed in two cups (Feigenson & Carey, 2005; Feigenson, Carey, & Hauser, 2002).

The ability to attend to the individual objects in a display disappears when infants are presented with arrays containing more than three objects. In such a case, infants do not notice the adding or removal of a single object but discriminate changes in overall numerosity. It is commonly believed that the representation of large numbers is only approximate and depends on the ratio between numerosities. Several studies confirm that infants discriminate static displays of dots differing in a 1:2 ratio (e.g., 4:8, 8:12, 16:24), but fail to do so when the ratio is 2:3 (e.g., 4:6, 8:12, 16:24 dots) (Brannon et al., 2004; Wood & Spelke, 2005; Xu, 2003; Xu & Spelke, 2000; Xu et al., 2005). Moreover, they correctly anticipate the outcome of an arithmetical event in dynamic displays when the ratio is 1:2 (e.g., 5:10) (McCrink & Wynn, 2004). By 10 months of age infants are able to discriminate dots in a 2:3 ratio (8:12 dots), but fail to discriminate 8 from 10 dots (i.e., 4:5 ratio, Xu & Arriaga, 2007). The ability to discriminate numerical proportions further improves during childhood (Cantlon, Libertus et al., 2009; Halberda & Feigenson, 2008), culminating in the adults' ability to discriminate arrays of dots in a 7:8 ratio (Barth, Kanwisher, & Spelke, 2003; Van Oeffelen & Vos, 1982).

These findings suggest that adults' ANS for large sets and the indexing of small sets may be available to infants (Cantlon, Platt, & Brannon, 2009; Carey, 2001; Carey & Xu, 2001; Cheries et al., 2009; Dehaene, Dehaene-Lambertz, & Cohen, 1998; Feigenson et al., 2004; Gallistel & Gelman, 2005; Spelke & Kinzler, 2007). The object indexing theory describes infants' processing of small sets most elaborately (Leslie et al., 1998; see also Scholl & Leslie, 1999). This theory draws parallels between infants' success in representing small numbers of objects and adults' object-based attention. Empirical evidence of striking similarities in infants' object concept and adults' object tracking supports this assumption. Both, infants' persistent representation of discrete objects and adults' attentive object tracking, outlast occlusion (Scholl & Pylyshyn, 1999). Further, infants' building of representations of discrete objects (i.e., the process of object individuation) is feature-blind at first and predominantly based on spatiotemporal criteria (Simon et al., 1995; Xu, 1999), as is adults' object based-attention (e.g., Pylyshyn, 2001). Yet, both processes are sensitive to substance kind of an entity. That is, both processes apply to rigid, bounded objects and fail in the face of unbound substance (Cheries et al., 2008; Huntley-Fenner et al., 2002; Mitroff et al., 2004; vanMarle & Scholl, 2003; vanMarle & Wynn, 2011; Wynn et al., 2002). Most importantly for the present study and as outlined above, both infants' object representations and adults' object-based attention are subject to a set size limit. According to the object indexing theory infants' representation of multiple object is not based on a process of enumerating or the application of arithmetical principles (e.g., Wynn, 1995). Instead, indexes are assigned to each presented object. These indexes stay active while the objects are hidden behind an occlusion screen. If upon lowering of the screen an object is missing, an active object index lacks its actual counterpart, which results in a search for the missing object. Analogously, if another object has been added to the hidden object, a novel index needs to be created when the screen is removed. In either case, overt visual attention needs to be allocated to the event in order to either search for the missing or create the novel index (e.g., Leslie et al., 1998; Scholl & Leslie, 1999; Simon, 1997).

In sum, it is agreed upon that the process involved in representing large numbers is unchanging over the course of life. This claim is based on findings from analogous tasks addressing infants' and adults' large-number representations. However, the claim that similar processes act upon small number representations in adults and infants is based on results from studies employing different tasks and methods between the age groups. For instance, habituation procedures presented static displays of objects while objects must be tracked through motion in multiple-object tracking tasks for adults. Studies using the violation of expectation paradigm presented infants with moving objects. However, these studies use long periods of occlusion. When adults' multiple object tracking tasks involve occlusions (most do not), the occlusion time is usually much shorter (i.e., 60-2640 ms, see Scholl & Pylyshyn, 1999) than in infants studies (e.g., 5 s in Simon et al., 1995). Consequently, adults' tracking might be purely based on attentional processes. Instead, infants must store the information for a longer period of time, which, in addition to attentional systems, might involve memory systems such as short-term memory in order to correctly analyze the unfolding event (Carey & Xu, 2001; Feigenson, 2007). Similarly, a prolonged period of occlusion was used in action-based tasks employed with infants (e.g., Feigenson & Carey, 2005). Given these differences, the evidence for a shared mechanism for small number representations in infants and adults is indirect and tentative at best. The present study aimed at directly comparing infants' and adults' tracking of multiple discrete objects by using the same experimental paradigm for both age groups. Animated moving dots were presented in varying numbers. All dots passed through a short occlusion and the detection of an additional dot was assessed. If participants tracked the dots as individuals they should notice the change and demonstrate increased attention towards the display with the novel dot. By contrast, if they do not track individual dots they should not notice the appearance of the additional dot. Attention to the novel dot was measured by means of an eye-tracking device, which allows both the precise measurement of the location as well as of the duration of gazes.

4.3 Method

The looking pattern of two groups of participants was compared. One group observed how, after a short period of occlusion, one dot was added to a collection of 1, 2, 3, 4, 5, or 6 moving dots (experimental condition). Participants of the second group (control condition) observed the very same events with one exception: the dot that was added after the occlusion in the experimental condition was part of the collection from the beginning of the events in the control condition. That is, no dot was added in the control condition.

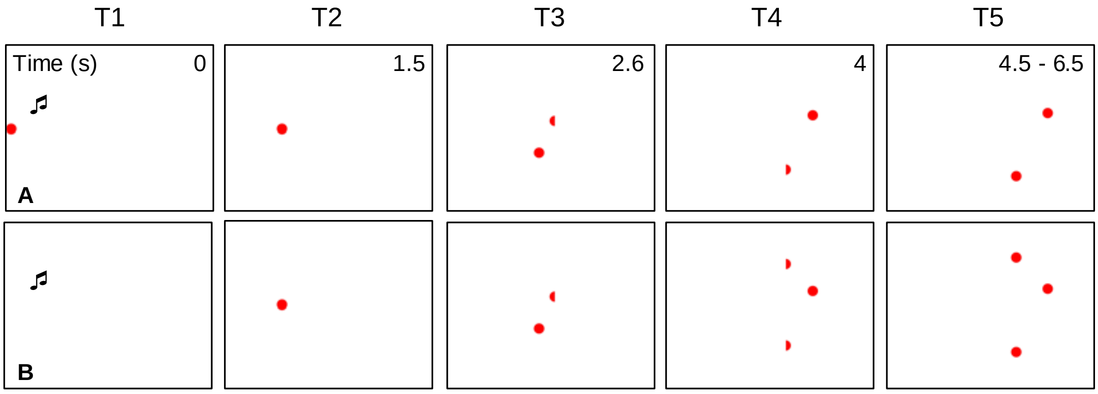

Figure 10. Sample frames in sequence from the experimental condition in a 2-dot event. The time line corresponds to the appearance of the respective frame. The first loop (A) introduced the 2 dots. In the second loop the target additionally appeared from behind the occluding bar (B). The events in the control condition were similar to loop B, except that the target was present from the beginning.

4.3.1 Participants

Twenty-one adults (mean age = 25 years 8 months) and 59 infants (mean age = 10 months 17 days *SD* = 8 days) participated in the study. Eleven additional participants had to be excluded due to unsuccessful calibration (1 adult, 1 infant), unwillingness to participate (1 infant), and less than 40 percent attention to the events (2 adults, 6 infants).

4.3.2 Stimuli and Apparatus

Stimuli were created with flash CS3 software. In the experimental condition, each trial containing one of the six numbers of dots (1 to 6 dots) was presented in two loops (see Figure 10 for an example). All loops began with the motion of a single dot in order to equalize direction of gazes and to constrain the direction of gazes towards all appearing dots. In the first loop, this red dot with a diameter of 2.7 cm (subtending 2.4° visual angle) appeared on the left-hand side in the middle of a 30″ computer screen.

The dot moved horizontally to the right with a constant speed of 9 cm/s (7.9°/s). After 1.5 s the dot started moving toward a final position, where it rested for 2 s. In events containing a larger number of dots (2 to 6), the initial dot started to divide into the respective number of dots after 1.5 s, each of which moved to a particular final position. Before reaching the final positions all dots passed behind an invisible occluding bar and were invisible for 42 ms. Figure 10 shows the example of a 2-dot event. First, in loop 1 (A) the single initial dot moves horizontally from its starting position in T1 to the position in T2. Next, the initial dot starts to divide in two dots and each dot moves to its final positions in T5. Note that the upper dot is partly occluded at T3 and the lower dot is partly occluded at T4. At this point, these dots pass behind the occluding bar. The second loop was similar to the first loop, except that one additional dot appeared from behind the occluder (target, see B in Figure 10: the upper, third dot is not visible before the occlusion).

The control condition differed from the experimental condition in that each trial consisted of only one loop. This loop was similar to the second loop in the experimental condition, except that the target was present throughout the whole event.

The final positions of the dots corresponded to the centers of 12 squares in a virtual grid (see Figure 11). This grid contained four segments on the y-axis, and three segments on the x-axis. The 1 to 6 dots (plus 1 target, each) were randomly assigned to the grid in four different layouts (see Figure 11 for a sample layout).

However, restrictions were placed on the assignments. First, the target was at only one of two positions. In half of the trials it appeared at the top left (high target), in the other half at the bottom left (low target). Second, no dot was placed next to the target in order to prevent from random looking at the target.

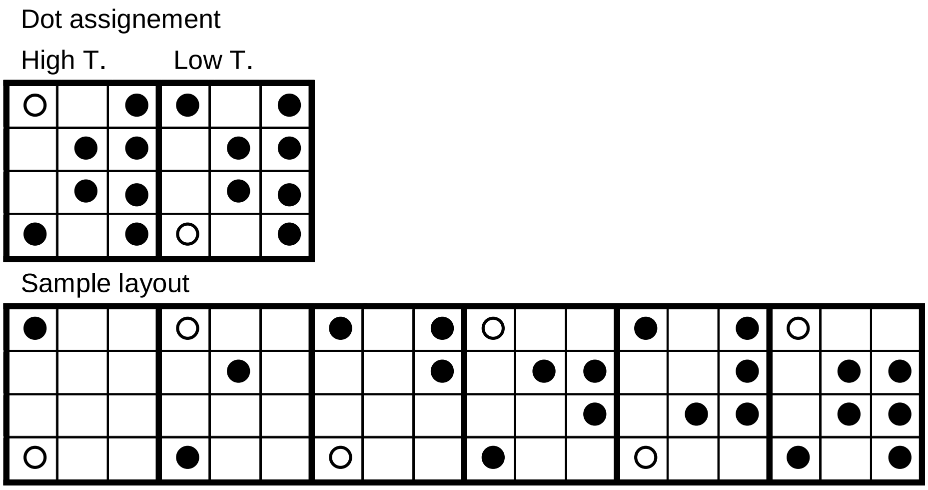

Figure 11. Depiction of the virtual grid for the two target positions (white) and the possible final positions of the initial dots in both cases (black), and one example of a layout of the six numbers.

In both conditions a blank screen was shown for 1.5 s in between all loops and each trial began with an attention getter (i.e., a green border flashing around the dot accompanied by a tingling sound for infants; only the audible attention getter for adults) Moreover, the second loop in the experimental condition of the infant age group started with the audible attention getter only.

4.3.3 Design

The target position alternated between the high and the low position in all four layouts and presented the six numbers of dots in two random orders. Also, the low target was added to odd numbers (1/3/5) and the high target to even numbers (2/4/6) in two of the four layouts. Two layouts presented the opposite (i.e., low target added to even numbers and high target added to odd numbers). Overall, this resulted in a 6 (number) × 2 (layout) × 2 (target position) within-subject design. However, due to time restrictions infants in the experimental condition watched only half the trials (i.e., each trial consisted of two loops) and layout was varied between subjects. A larger sample was thus assigned to the experimental condition (n = 36) than to the control condition (n = 23). Adults in the control condition watched each trial twice.

4.3.4 Procedure

The events were presented on a 69.5 cm wide and 46 cm high computer monitor. Participants faced the center of the monitor in a viewing distance of approximately 65 cm. Infants sat in a Bumbo baby seat (Bumbo (Pty) Limited, Rosslyn, Gauteng, South Africa) that was placed on a height adjustable table. The events were presented in two sessions, with a break in-between. In the experimental condition each session consisted of 6 trials (105.5 s). In the control condition each session consisted of 12 trials (114.5 s). Adults sat on a chair in front of the monitor and watched the 24 trials (experimental condition) or 48 trials (control condition) in one session, lasting 385 s. Adults received no instruction except “please watch the film”. However, they were informed that these films were also shown to infants.

Gaze was measured using a Tobii eye-tracking system, which was positioned below and in front of the computer monitor. The tracker illuminates both eyes with an infrared light and captures the reflection in the pupil and cornea. These recordings allow the determination of the fixation point at any given time. Before presenting the animations, a calibration procedure was carried out. A sounding figure appeared at nine calibration points for the infants, and a blue dot passed the same calibration points for the adults. Unsuccessful calibration points were presented again.

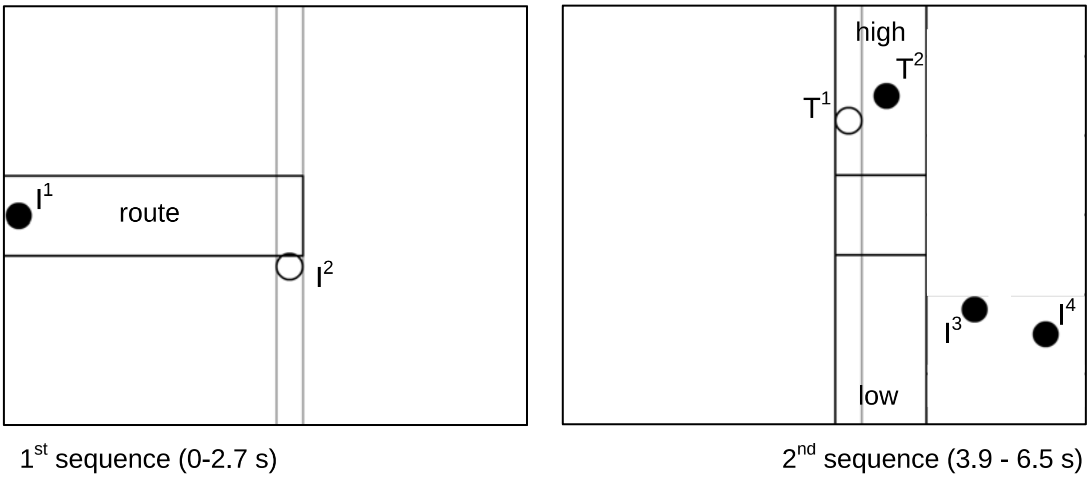

Figure 12. The left picture depicts the AOI of an example on an initial dots' (I) route during the first sequence (1-dot event), from the starting position (I^1) to the disappearance behind the occluding bar (I^2). The right picture depicts the two AOIs of interest (high and low target) beginning with the fully occluded target (T^1; plus the initial dot, I^3), and ending with the disappearance of all dots at their final position (T^2 and I^4). Note that neither the dots behind the bar nor the occluding bar were visible in the actual events.

4.3.5 Analyses

Each loop was divided in two sequences (see Figure 12). The first sequence lasted from the initiation of motion at the far left to the disappearance of the outer right dots behind the occluding bar (2.7s). The second sequence began with the initiation of motion of the target behind the occluding bar and ended with the disappearance of the dots (2.6 s). Areas of interests (AOIs) were defined for both sequences. The AOI defined for the first sequence was 8.2 cm (7.2°) high and 30.6 cm (26.5°) wide (i.e., left end of the screen to the end of the occluding bar). The second sequence was divided in two AOIs according to the virtual grid presented in Figure 11. One AOI covered the upper space (high target) and one covered the lower space (low target). Both AOIs measured 16 cm (14.0°) in height and 9.4 cm (8.3°) in width. In the experimental condition it was essential that participants were tracking the dots' movement before they disappeared behind the occluding bar. Otherwise, they would not have noticed the appearance of an additional dot. Therefore, looking times were not considered in the analysis of the second sequence when infants were not attending to the first sequence. Two measures were calculated for each participant and trial in the second sequence: the total fixation time at the screen during the 2.6 s period, and the fixation time spent on the target. Figure 13 shows an example of infants' and adults' fixations during the second sequence. Missing values were replaced by the respective group mean.

4.4 Results

An initial comparison of total looking time during the second sequence (cf. Figure 12) revealed no differences between the two conditions (experimental and control) in the overall sample (adults and infants), $F(1, 78) = .03$, $p = .86$, in the infant sample, $F(1, 57) = .15$, $p = .70$, or in the adult sample, $F(1, 19) = .12$, $p = .73$. Therefore, absolute looking times at the target were analyzed in the following analyses.

Preliminary analyses of looking times at targets revealed no effects of layout, order, or sex. These variables needed to be analyzed for the different groups separately, because layout was a between subject variable in the experimental group of the infant sample. In the adult sample the mixed measures analyses of variance

(ANOVA) with 6 (number) × 2 (target position) × 2 (layout) as within subject variables and 2 (condition) × 2 (order) × 2 (sex) as between subjects variables revealed no effect of layout, $F(1, 13) = 1.10$, $p = .31$, $\eta_p^2 = .08$, or interaction of layout × condition, $F(1, 13) = 2.36$, $p = .15$, $\eta_p^2 = .15$, of sex, $F(1, 13) = .24$, $p = .63$, $\eta_p^2 = .02$, or order, $F(1, 13) = .33$, $p = .57$, $\eta_p^2 = .03$. In the control condition of the infant sample the ANOVA with 6 (number) × 2 (target position) × 2 (layout) as within and 2 (order) × 2 (sex) as between subjects variables revealed no effect of layout, $F(1, 19) = 1.04$, $p = .32$, $\eta_p^2 = .05$, sex, $F(1, 19) = .90$, $p = .36$, $\eta_p^2 = .05$, or order, $F(1, 19) = .22$, $p = .64$, $\eta_p^2 = .01$. Finally, the ANOVA with 6 (number) × 2 (target position) as within and 2 (layout) ×2 (order) × 2 (sex) as between subjects variables analyzing infants' looking times in the experimental condition revealed no effects of layout, $F(1, 26) = 2.85$, $p = .10$, $\eta_p^2 = .10$, sex, $F(1, 26) = 1.07$, $p = .31$, $\eta_p^2 = .04$, or order, $F(1, 26) = .04$, $p = .85$, $\eta_p^2 = .001$. Looking time data were therefore collapsed over layout, order, and sex.

The main interests of the current study were differences in looking times at the target in the two experimental conditions. That is, looking times at the target should be longer in the experimental condition (i.e., target = novel) than in the control condition (i.e., target = familiar). The main analysis therefore analyzed looking times at the target with a 6 (number) × 2 (target position) × 2 (condition) × 2 (age group) ANOVA. Overall, the expected effect of condition was found, $F(1, 76) = 29.08$, $p = .000$, $\eta_p^2 = .28$. Looking times at the target were longer in the experimental (.71 s) than in the control condition (.43 s). However, the analysis revealed further main effects of target position, $F(1, 76) = 63.75$, $p = .000$, $\eta_p^2 = .46$, number, $F(5, 380) = 63.85$, $p = .000$, $\eta_p^2 = .46$, and age group, $F(1, 76) = 10.48$, $p = .002$, $\eta_p^2 = .12$. The subsequent sections will analyze these effects more closely and report interactions between these variables.

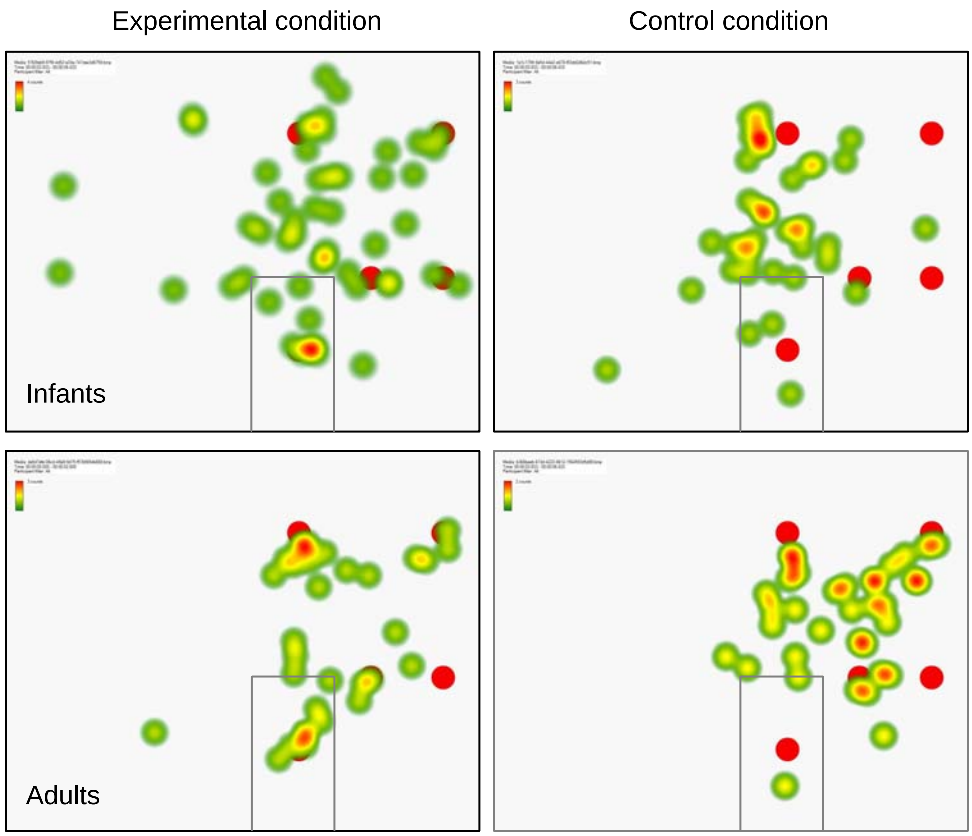

Figure 13. Heat map visualization of participants' looking patterns during the final 2.6 s period of a loop with four dots plus one target appearing in the low position. The grey square depicts the area where fixation times were measured (AOI).

4.4.1 Target Position

The main effect of target position in the overall ANOVA was based on longer looking times at the high target (.74 s) compared with the looking times at the low target (.40 s). Also, the ANOVA revealed a significant interaction of age group × target position, $F(1, 76) = 6.52$, $p = .01$, $\eta_p^2 = .08$. This interaction will be analyzed more closely in the section reporting the separate analyses of the two age groups. In order to further analyze the effect of target position 6 (number) × 2 (condition) ANOVAs were conducted for the two target positions separately.

Table 2

Mean looking times at targets overall (T), in the experimental (E) and the control condition (C), and statistical values for the effects of condition

Sample	Number	T	E	C	*F*	*p*	η_p^2
Overall	1	.92	.89	.94	.24	.62	.003
N = 80	2	.76	.89	.63	7.02	.01	.08
	3	.55	.72	.37	16.58	.000	.18
	4	.48	.68	.27	21.02	.000	.21
	5	.37	.50	.24	3.15	.08	.04
	6	.35	.56	.14	31.22	.000	.29
Infants	1	.77	.78	.75	.11	.74	.002
n = 59	2	.77	.82	.71	2.10	.15	.04
	3	.51	.59	.42	5.53	.02	.09
	4	.38	.51	.24	15.99	.000	.22
	5	.26	.25	.26	.04	.84	.001
	6	.26	.39	.12	23.83	.000	.30
Adults	1	1.07	1.01	1.13	.51	.48	.03
n = 21	2	.76	.97	.55	5.44	.03	.22
	3	.59	.85	.32	21.02	.000	.53
	4	.57	.86	.29	9.24	.007	.33
	5	.48	.74	.22	9.77	.006	.34
	6	.44	.72	.17	15.00	.001	.44

However, despite the overall longer looking times at the high target, these analyses revealed the same looking pattern for both target positions. That is, we found a main effect of condition for the high target (.77 s/.56 s), $F(1, 78) = 7.74$, $p = .007$, $\eta_p^2 = .09$, as well as for the low target (.48 s/.29 s), $F(1, 78) = 16.25$, $p = .000$, $\eta_p^2 = .17$.

4.4.2 Number

As can be seen in Table 2, the main effect of number in the overall ANOVA was due to declining looking times from 1-dot events to 6-dots events. Furthermore, number interacted significantly with condition, $F(5, 380) = 9.53$, $p = .000$, $\eta_p^2 = .11$. We therefore analyzed effects of condition for each number separately by the means of 2 (target position) × 2 (condition) ANOVAs. The effects of condition can be read in Table 2. The expected differences between the conditions (i.e., longer looking times at the target in the experimental condition) were found in the case of 2-, 3-, 4- and 6-dot events. No differences between the two conditions were found in the case of 1- and 5-dot events. Also, these analyses revealed main effects of target position due to the reported preference for the high target. In 6-dot events target position additionally interacted significantly with condition, $F(1, 78) = 6.30$, $p = .01$, $\eta_p^2 = .08$. However, participants from the experimental condition looked longer at the target when it appeared in the high position (.67 s/.21 s), $F(1, 78) = 23.00$, $p = .000$, and when it appeared in the low position (.27 s,/.06 s), $F(1, 78) = 15.67$, $p = .000$.

4.4.3 Age Group

Apart from the main effect of age group in the overall ANOVA a significant interaction of age group × number was found, $F(5, 380) = 3.79$, $p = .002$, $\eta_p^2 = .05$.

However, looking times mainly declined from 1-dot to 6-dot events in both age groups (see Table 2). Also, the analysis revealed a significant interaction of age group × condition, $F(1, 76) = 6.99$, $p = .01$, $\eta_P^2 = .08$, a three-way interaction of age group × number × condition, $F(5, 380) = 3.96$, $p = .002$, $\eta_P^2 = .05$, and a four-way interaction of age group × number × target position × condition, $F(5, 380) = 3.07$, $p = .01$, $\eta_P^2 = .04$. We computed 6 (number) × 2 (target position) × 2 (condition) ANOVAs for the two age groups separately, to address these interactions. However, despite the age effects in the overall ANOVA similar effects were revealed in both age groups.

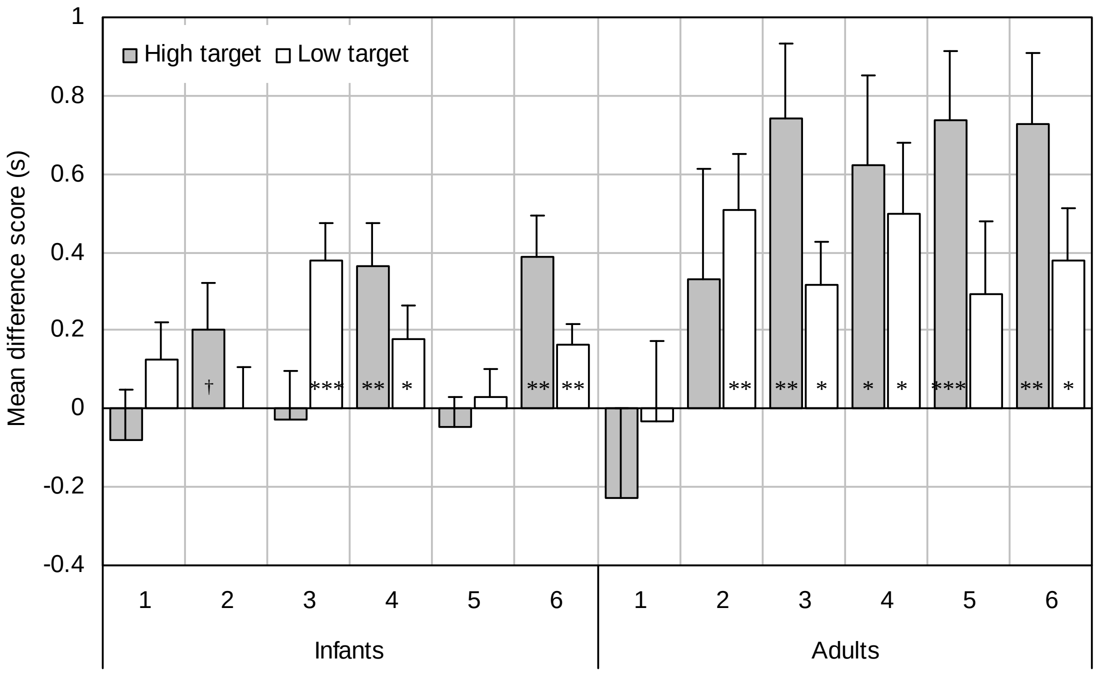

Figure 14. Mean differences in looking times between the experimental and the control condition (experimental-control) for the six numbers and the two target positions.

Essentially, we found the expected effect of condition in the infant (.56 s/.42 s), $F(1, 57) = 14.87$, $p = .000$, $\eta_P^2 = .21$, and in the adult sample (.86 s/.45 s), $F(1, 19) = 8.53$, $p = .009$, $\eta_P^2 = .31$. Further, a main effect of number was revealed in the analysis of infants' looking times, $F(5, 285) = 61.22$, $p = .000$, $\eta_P^2 = .52$, and in the analysis of adults' looking times, $F(5, 95) = 25.06$, $p = .000$, $\eta_p^2 = .57$. Both age groups looked longest at 1-dot events and shortest at 6-dot events (see Table 2). Finally, a main effect of target position was found in the infant sample (high: .60 s, low: .38 s), $F(1, 57) = 26.31$, $p = .000$, $\eta_p^2 = .32$, and in the adult sample (high: .87 s, low: .43 s), $F(1, 19) = 42.05$, $p = .000$, $\eta_p^2 = .69$.

Separate analyses were conducted for the two target positions in each age group. In the infant sample, condition was marginally significant for the high target (.67 s/.54 s), $F(1, 57) = 3.74$, $p = .06$, $\eta_p^2 = .06$, but reached significance for the low target (.45 s/.30 s), $F(1, 57) = 11.83$, $p = .001$, $\eta_p^2 = .17$. In the adult sample condition was a main effect for the high target (1.12 s/.63 s), $F(1, 19) = 7.78$, $p = .01$, $\eta_p^2 = .29$, and for the low target (.60 s/.27 s), $F(1, 19) = 6.10$, $p = .02$.

The separate analyses of the two age groups further revealed similar interactions. That is, a significant interaction of number × condition was found in the infant sample, $F(5, 285) = 4.09$, $p = .001$, $\eta_p^2 = .07$, and in the adult sample, $F(5, 95) = 8.40$, $p = .000$, $\eta_p^2 = .31$, as well as a three-way interaction of number × condition × target position was found in the infant sample, $F(5, 285) = 3.62$, $p = .003$, $\eta_p^2 = .06$, and in the adult sample, $F(5, 95) = 3.03$, $p = .01$, $\eta_p^2 = .14$. We conducted separate 2 (target position) × 2 (condition) ANOVAs for each number to address this interaction. In the infant sample the expected differences between the two experimental conditions (i.e., longer looking times at the target in the experimental condition) were found for 3-, 4-, and 6-dot events. In the adult sample the expected differences were found in all but the 1-dot event (see Table 2 and Figure 13, for an example of the looking pattern at a 4-dot event). Participants looked longer at the target in the high than in the low position with one exception: Target position was not significant in the infant sample in 5-dot events, $F(1, 57) = 1.76$, $p = .19$, $\eta_p^2 = .03$. Further, position interacted significantly with condition in 3-dot events in the infant sample, $F(1, 57) = 5.62$, $p = .02$, $\eta_p^2 = .09$, 5-dot events in the adult sample, $F(1, 19) = 9.43$, $p = .006$, $\eta_p^2 = .33$, and 6-dot events in the adult sample, $F(1, 19) = 6.25$, $p = .02$, $\eta_p^2 = .25$. As can be seen in Figure 14 infants exhibited the expected preference in 3-dot arrays only when the target appeared in the low position. The expected preference in the adult sample was found in 6-dot events in either position. However, adults in the experimental condition looked longer at the target in 5-dot events only when it appeared in the high position. Looking times did not differ for the low target.

4.5 Discussion

Ten-month-old infants and adults noticed when a single item was added to a collection of items. These results suggest that our task is a valid measure of infants' object tracking abilities and feasible for the assessment of infants' and adults' object tracking system alike. It is important to note that the adult participants would most certainly have noticed the additional dot, were they instructed to do so (e.g., with a direct request to find the additional dot on the monitor). However, adult participants were merely told to watch the films, rendering them naïve towards the goal of this study. Moreover, telling adults that the viewing material was the same as the one presented to infants, may well have contributed towards their unbiased watching (i.e., prevented them from guessing the purpose of the study). Indeed, we found that adults did *not* look longer at target dots in all the events. Moreover, we found that in cases where the looking times between the experimental and the control condition did not differ, they mirrored the looking pattern of the infant sample. That is, consistent with the literature we found successful tracking of small numbers of items (3- and 4-dot events) and limited tracking in the case of 5-dot events (i.e., in the case of the low target in the adult sample). Furthermore and unexpectedly, we found successful tracking of a large number event (i.e., 6-dot events), as well as differential looking times depending on the target position.

The finding that infants and adults allocated enhanced interest (i.e., longer looking times) towards a novel dot in small number events is in line with previous research and supports theoretical claims as proposed for instance by the object indexing theory (Leslie et al., 1998; Scholl & Leslie, 1999). In contrast to previous studies examining the representation of multiple objects, the present task not only tested *if* infants noticed the addition of a dot (i.e., by measuring looking time at the scene overall) but also whether they detected *which* dot was added (i.e., by measuring the location of fixation). The enhanced interest towards the distinct location of the novel dot thus conforms to the claim that a novel index needs to be established for an appearing object.

The range of small number events in which infants identified the added object, however, exceeded our expectations. While a set size limit of four items is consistent with previous findings regarding adults' attentive tracking (e.g., Pylyshyn & Storm, 1988), and with their subitizing range (e.g., Kaufman et al., 1949), a set size limit of four items is remarkable in infants, and larger than it was in most of the previous research (i.e., three, see Cordes & Brannon, 2008; Feigenson et al., 2004; see Van Loosbroek & Smitsman, 1990, for an exception). In contrast to previous infant work, the current task might have been less demanding, thereby accounting for a higher set size limit in infants. For example, in the present study infants only needed to compare the size of one set of objects (as opposed to two sets in many of the previous studies) (e.g., Feigenson & Carey, 2005). Also, the single objects in the present study needed not to be represented over a prolonged period of occlusion (e.g., Feigenson & Carey, 2003; Wynn, 1992). That is, the moving dots could have been attended to without the necessity to store the single dots or the total set in the short-term memory (Carey & Xu, 2001). Note that the events did involve a short period of occlusion. However, both infants' and adults' attention towards a moving object outlast a short occlusion (e.g., Kochukhova & Gredebäck, 2007; Scholl & Pylyshyn, 1999). A potential caveat to this interpretation is that infants' looking times did not reliably differ between experimental and control condition in the case of 1- and 2-dot events (and in the case of 1-dot events in the adult sample). However, we think it is save to conclude that this finding does not indicate that infants failed to detect the novel dot in the case of 1- and 2-dot events, or adults in the case of 1-dot events, but is brought about by a floor effect. That is, the novel dot constituted one of only two, (or one of only three) visible dots and looking times in the control condition at these dots were therefore long, as well (simply because there was nothing else to look at).

Unexpectedly, both age groups detected the target in 6-dot events. We rule out the possibility that success was based on the tracking of individual dots for the following reasons. First, six objects clearly exceed even adults' span, within which they can attend to objects in parallel (e.g., Pylyshyn & Storm, 1988). Second, if the small number system was used to solve the 6-dot task, similar results should have been obtained in the set including five dots. Third, it seems unlikely that success was based on the tracking of a subset of dots. Again, if this would have been the case we should have observed successful discrimination in 5-dots events, as well.

However, it is conceivable that successful tracking of six but not five dots may be explained by a change in strategy when confronted with a number *exceeding* the capacity limit as opposed to a number *within* the capacity limit. Within such a strategy-change account it might be argued that the confrontation with six dots led to the application of a novel strategy—namely, grouping the single objects into one group. Parallels to our findings were reported in a study on adults' multiple-object tracking by Oksama and Hyönä (2004) where adults' accuracy in tracking unpredictably moving target items among distractors was more accurate for six target items than it was for five target items. Moreover, previous work has shown that also infants build groups of multiple objects and track these groups as individuals themselves (Wynn et al., 2002). It is thus possible, that also infants and adults in the present study perceived the large number of six dots as one single group. Based on this argument, the tracking success in 6-dot events was not based on six (dots) plus one, but instead on one (group) plus one. What could account for such a strategy change in the case of six, but not in the case of five dots? Or in other words—why did the perceptual grouping strategy not guide infants' and adults' behavior in 5-dot events, as well? In fact, there are several reasons that render it more likely that six (but not five) dots are perceived as one group. First, perceptual grouping is strongly determined by Gestalt laws (e.g., Beckwith & Restle, 1966; Kahneman & Henik, 1977; Quinn, Bhatt, & Hayden, 2008; Treisman, 1982). Given the higher visual density, 6-dot events thus accord to the Gestalt law of proximity more than 5-dot events. Furthermore, perceived regularity among a group of dots favors group processing (Wagemans, Van Gool, Swinnen, & Van Horebeek, 1993; Feldman, 1997). Even numbers (such as six) might therefore favor perceptual grouping over odd numbers (such as five) because only even numbers offer the possibility to build regular groups. Related to the regularity argument, infants are indeed able to build perceptual chunks of even numbers (i.e., three sets of two, Feigenson & Halberda, 2008; see also Feigenson & Halberda, 2004). Together, these factors might explain why the grouping strategy arose in the case of 6-dot events, but not in the case of 5-dot events.

Future research is needed to determine whether a grouping process was responsible for the detection of the additional dot exclusively in 6-dot events. In the present events, the target dot always appeared outside the outer contour of the initial group of dots. Therefore, this dot was easy detectable if the six dots were grouped. This should not be the case when the target dot appears *within* the initial group of dots. In this case the target dot should not be detected because it is engulf within the other dots.

The second unexpected finding is that looking times at the high target were generally higher. Considering the similar overall patterns in the arrangements of the dots, and that the visual angles for the high and the low target dot were equal, we did not expect different looking times for the two target positions. However, there is evidence from vision research that visual attention does not spread equally across the field. Specifically, this research shows discrepancies in the vertical axis, between the upper and the lower visual field (e.g., Rubin, Nakayama, & Shapley, 1996; Talgar & Carrasco, 2002). While these research findings do not fully explain our observed preference for the high dot, they might be a starting point for future studies on the issue of target position effects. More importantly to the current study, target position did not affect the overall pattern of looking times (i.e., the differences between the control and the experimental group).

To summarize, we found similar looking patterns in infants and adults who watched the same events. First, we found a similar set size limit of four in both age groups. This finding supports previous claims of parallels in infants' and adults' processing of small sets of objects (e.g., Carey & Xu, 2001; Cheries et al., 2009; Leslie et al., 1998). Second, we found the same patterns of successes and failures in both age groups. That is, we found success in the case of small numbers, limited tracking in the case of 5-dot events, and success in the case of 6-dot events. On the basis of these findings it seems unlikely that one and the same mechanism is responsible for the tracking of both small and large numbers of items. Instead, these results support the assumption that a distinct process of object-based attention acts on small sets of objects only. As noted above, the nature of mechanisms underlying the successful tracking of six dots must be further addressed in future studies.

5. STUDY III[3]

5.1 Abstract

The present study investigated whether or not infants appreciate that shape changes indicate identity changes in rigid objects but not in non-solid substances. Twelve-month-old infants observed how either a rigid object or a non-solid substance was placed in a box. When searching the box they retrieved either an object/substance with the same (no-switch event) or with a different shape (switch event). Infants' re-searching behavior indicated that they appreciated that shape invariance is a property of rigid objects only. They thus correctly inferred two distinct objects in the switch event in the case of rigid objects. In contrast to that, shape was not perceived as a defining property of a non-solid substance.

5.2 Introduction

An elementary classification of the physical world is the distinction between objects and substances. Objects refer to individuated entities in our surroundings and *object kind* is typically defined by shape (e.g., that chair). Substances, by contrast, refer to non-individuated entities and *substance kind* may not be defined by shape (e.g., some wood). This specifically applies to non-solid substances which fail to adopt a permanent shape altogether. For example, a currently perceived square-shaped piece of clay might have been a round-shaped piece of clay a minute ago. Developmental research revealed that infants appreciate that shape is a basic and enduring property

[3] A similar version of this chapter is submitted for publication as: Schaub, S., Bertin, E., & Cacchione, T. Infants' individuation of rigid and non-solid substance based on shape in a manual search task.

of physical objects (e.g., Baillargeon & DeVos, 1991; Baillargeon et al., 1985; Spelke et al., 1992). They use shape as a basis for object individuation (i.e., the identification of the number of objects present in an event) (see Krøjgaard, 2004; Xu, 2005, for reviews). Furthermore, infants appreciate that substance is an enduring property of physical entities. That is, infants appreciate that a rigid substance cannot transform into a non-rigid substance, and vice versa (e.g., Gibson et al., 1979). The present study sets out to investigate further, how infants bring to bear their physical knowledge about material properties of solid objects and non-solid substances in an individuation context. Particularly, we intended to find out more about infants' ability to differentiate between shape changes that constitute transformations in numerical identity (as is the case with solid objects) and those that do not (as is the case with non-solid substances).

A vast body of research shows that solid objects are the basic unit of many processes of infants' perceptual and cognitive reasoning (e.g., Carey & Xu, 2001; Scholl & Leslie, 1999; Spelke, Vishton et al., 1995). Object individuation describes the process of how representations of distinct objects are formed. This elementary process establishes the unit upon which perceptual and cognitive processes functions. Seemingly effortless object individuation may be based on a number of criteria in adult observers (Van de Walle et al., 2000). For instance, we would not mistake our car for a different model (i.e., kind change), for the same model with a different color (i.e., property change), or for the same model with the same color but found in a different parking space (i.e., spatiotemporal change). Infancy research points to a developmental course in the application of these individuation criteria.

Spatiotemporal information offers an unequivocal criteria for individuation and even very young infants appreciate that one object cannot be at two places at the same time (e.g., Aguiar & Baillargeon, 1999; Spelke, Kestenbaum et al., 1995; Van de Walle & Spelke, 1996; Wynn, 1992). Only later in development will infants individuate objects on the basis of property information (e.g., shape, color, or texture) (e.g., Needham, 1998; Tremoulet et al., 2000; Wilcox, 1999) and kind information (e.g., toy/dish) (e.g., Bonatti, Frot, Zangl, & Mehler, 2002; Kingo & Krøjgaard, 2011; Van de Walle et al., 2000; Xu & Carey, 1996; Xu & Baker, 2005).

A growing body of research demonstrates that the individuation process in infants is influenced by material properties of objects. Particularly, it is suggested that individuation functions preferably over entities that are solid and bound (e.g., Cheries et al., 2008; Chiang & Wynn, 2000; Huntley-Fenner et al., 2002; vanMarle & Wynn, 2011). For instance, Huntley-Fenner et al. found that infants were unable to individuate non-cohesive entities (i.e., sand) based on apparent spatiotemporal criteria (i.e., two sand piles). However, the same study bore evidence to the fact that individuation is not restricted to solid entities. Infants succeeded in individuating two portions of a non-rigid, bound substance (i.e., a soft molding compound) that were lowered at two distinct hidden places. That is, despite the constant shape change of this substance, infants' representations of individual portions were not disrupted. While this study demonstrates that shape changes do not disrupt infants' representation of an entity, none of the previous work addressed infants' expectations towards the shape changes themselves.

At present, research on infants' expectations about the physical properties of non-solid substances is rather sparse. While infants appear to have a sophisticated understanding of the natural behavior of liquids (e.g., penetrability) (Hespos et al., 2009; see also Gao et al., 2000), they seem to have no grasp of the physical properties underlying aggregates (e.g., the non-cohesiveness of sand) (Huntley-Fenner, 1995; in Rosenberg & Carey, 2009). Similarly, little is known about whether or not infants appreciate that shape invariance is a property restricted to solid objects. Nevertheless, previous research has shown that infants appear to hold some knowledge of the physical behavior of soft objects. For example, they are sensitive to softness (i.e., elasticity) as an invariant property of objects, which they infer from characteristic motion parameters (e.g., Walker et al., 1980). Furthermore, they rely on this knowledge when predicting the outcome of mechanical interactions (e.g., Aguiar & Baillargeon, 1998; Baillargeon, 1987; Schweinle & Wilcox, 2004). However, the soft objects used in these studies spontaneously resumed their normal shape after deformation. That is, these studies did not address infants' expectations towards non-solid substances that change their shape permanently.

To summarize, infants appreciate that shape constitutes an enduring property of solid objects and that shape properties may be relied upon to individuate distinct objects. Furthermore, infants appreciate that substance is an enduring property of physical entities and that spatiotemporal information may be used to individuate distinct portions of substances. However, it remains an open question of whether or not infants appreciate that shape changes indicate identity changes in solid objects but not in non-solid substances. To address this question we employed a plastic substance (i.e., clay). In contrast to many of the non-solid substances used in previous studies (e.g., sand, water), a plastic substance may adopt and keep any shape. In contrast to soft objects (which spring back into their original shape after pressure is released), an external force may easily and permanently change the shape of a plastic substance. Further, a manual search procedure similar to the one used by Xu and Baker (2005) was employed. Two groups of 12-month-old infants observed how either a rigid object (rigid condition) or a non-solid substance (i.e., a piece of clay; non-solid condition) was placed in a box. When searching the box they retrieved either an entity with the same (no-switch event) or with a different shape (switch event). We hypothesized that if infants appreciated that shape invariance is only a property of rigid objects but not of non-solid substances, they should infer two numerically distinct objects in the switch event of the rigid but not the non-solid condition. Thus, we expected infants to re-search the box longer after retrieving a switched entity in the rigid condition only.

5.3 Methods

5.3.1 Participants

The final sample consisted of 32 healthy, full term 12-month-old infants (mean age = 366 days, SD = 11 days). Seventeen of the infants were girls. Twelve additional infants had to be excluded due to experimenter error (3), fuzziness (3), unwillingness to reach inside the box (3) and parental interference (3).

5.3.2 Materials

Stimuli were made of pink modeling clay. The clay was dried to hardness in the rigid condition and kept deformable and soft in the non-solid condition. Thus, the stimuli in the two conditions looked identical and differed only in their ability to deform. Clumps of clay and flattened clay-balls were used in the familiarization phase. Test stimuli were clay "sausages" (thereafter called "I"-shape, 10 cm long, 2.4 cm in diameter) and the same clay "sausage" made into a "U"-shape. In the rigid condition, the I- and the U-shapes were hard and solid; in the non-solid condition they were soft and potentially deformable. The stimuli were placed inside a 26 cm wide × 34 cm deep × 18 cm high wooden box. An opening measuring 15 × 9 cm in the front wall of the box was covered with a pink spandex material with a horizontal slit across its width.

Infants were randomly assigned to the rigid or the non-solid condition. In both conditions, infants received one switch test trial and one no-switch test trial. In switch trials, infants observed how one shape (e.g., U-shape) was placed in the box and a different shape (I-shape) was retrieved from the box. In no-switch trials, the stimuli that went in and out of the box were identical. Order of test trials (switch/no-switch) and shape of the first test stimulus (I/U) were counterbalanced across infants.

5.3.3 Procedure

Infants sat on their parents' lap in front of a 120 cm × 80 cm table. The procedure was identical in the rigid and in the non-solid condition except that the stimuli were made of fully hardened clay (i.e., rigid condition) or still deformable clay (i.e., non-solid condition).

The procedure began with a familiarization phase that acquainted infants with the stimuli and the box. First, infants were allowed to manipulate a clump of clay (i.e., hardened in the rigid condition, deformable in the non-solid condition) for 60 seconds. To ensure that infants performed object-distinctive actions (e.g., banging the rigid and kneading the non-solid clump of clay), parents were asked to guide their children.

Next, two trials familiarized the infants with the box. In the first trial the experimenter put the box at the far end of the table, took out a ball-shaped entity, placed it in front of the box, and pointed at it accompanied by the words "See this?". The ball was then placed into the box, so that it partially protruded through the slit in the front opening. Finally, the experimenter pushed the box in front of the infant and encouraged her or him to retrieve the ball by saying "It's your turn". The infant was allowed to handle the retrieved ball for 5 seconds while the box was placed back at the far end of the table. The second trial was similar to the first trial except that the ball was fully placed inside the box before the infant was encouraged to search for it. If infants did not reach inside the box, this procedure was repeated twice. That is, the familiarization phase ended as soon as the infant had retrieved the fully-inserted ball from the box at least one time. Once this was achieved, the experimenter removed the box and the ball outside of the infant's view.

The test phase consisted of three steps. First, the experimenter placed the box at the far end of the table, removed either the I- or the U-shaped test stimulus from the box, placed it in front of the box, pointed at it and said "See this?". Afterwards she placed the stimulus back inside the box and repeated this procedure one more time.

Second, the experimenter pushed the box in front of the infant upon which the infant was encouraged to retrieve the stimulus. The infant was allowed to explore the retrieved stimulus for 5 seconds while the experimenter placed the box back at the far end of the table. In the third and final step of the test phase, the experimenter took the stimulus from the infant and pushed the box back in front of the infant for a re-search period that lasted 10 seconds.

Thereafter, the box was taken out of the infant's view before the experimenter placed it back on the table for the second test trial. The critical difference between the *no-switch* and the *switch* test trials was the shape of the retrieved stimulus. In particular, the retrieved stimulus in the no-switch trials was identical to the one put inside the box by the experimenter (I-I/U-U). In switch trials, the infant retrieved a stimulus with a different shape (I-U/U-I). In these trials, the experimenter switched the stimuli by placing the ingoing entity at the far end of the box behind a small wall, out of infants' reaching distance. In order to give infants no cue as to the switching of stimuli, the experimenter imitated this hand movement in no-switch trials, as well.

5.3.4 Analyses

The dependent measure was the search time after the retrieved stimulus had been taken away from the infant and the box was placed in front of the infant for a second time (10 s re-search period). The 10-second period began when the infant's knuckles were entirely inside the front opening of the box. Searching times were coded from videotapes by an observer blind to the experimental condition and trial type.

A second observer coded duration of search for half of the infants. To compare the two ratings, difference scores between searching in switch and in no-switch trials were calculated for each child. The average inter-rater agreement was high (r = .95). Thus, the codings of the first observer were used in the statistical analyses.

5.4 Results

Preliminary analyses revealed no effects of order of test trials, shape of the first test stimulus or sex, so these variables were omitted from further consideration.

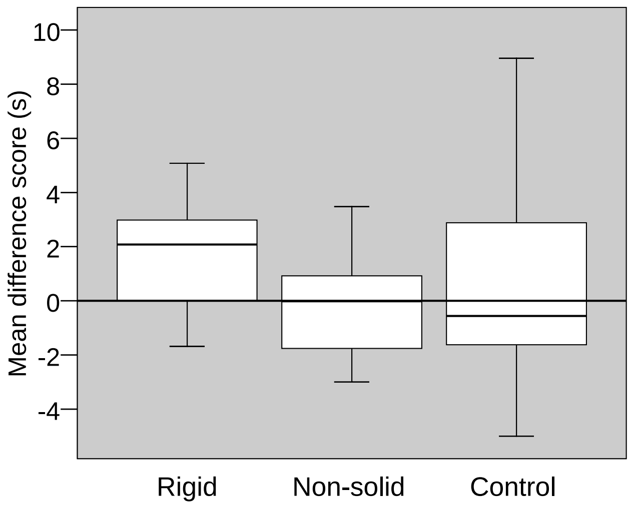

Figure 15. Box plots for mean differences between searching times in switch trials and in no-switch trials (switch/no-switch) in the three conditions. The central line represents the median; the upper and lower parts of the box the 75th and 25th quartiles on either side of the median.

A trial type (switch/no-switch) × experimental condition (rigid/non-solid) mixed measures ANOVA revealed a main effect of trial type, $F(1, 30) = 5.82$, $p = .02$, $\eta_p^2 = .16$, and a significant interaction of trial type × experimental condition, $F(1, 30) = 7.73$, $p = .009$, $\eta_p^2 = .21$. Infants searched longer in switch trials (M = 3.96 s, SD = 1.97) than in no-switch trials (M = 3.14 s, SD = 2.53). Separate analyses of the two conditions showed that only infants in the rigid condition searched longer in switch (M = 4.04 s, SD = 2.28) than in no-switch trials (M = 2.28 s, SD = 2.34), $t(15) = 3.73$, $p = .002$. This was confirmed by nonparametric analyses. Twelve of the 16 infants searched longer in switch than in no-switch trials, Wilcoxon z = 2.78, $p = .005$. Mean searching time of infants in the non-solid condition was 3.88 s (SD = 1.69) in switch trials and 4.01 s (SD = 2.47) in no-switch trials. These searching times did not differ statistically, $t(15) = -.26$, $p = .8$. Likewise, only half of the infants searched longer in switch trials, Wilcoxon z = .26, $p = .8$ (see also Figure 15).

5.5 Discussion

Infants re-searched the box longer after retrieving an entity that changed its shape. However, they only did so in the rigid condition. This suggests that infants were able to individuate rigid objects on the basis of their shape. Further, this result suggests that infants appreciated that shape invariance is a property restricted to rigid objects. Thus, they correctly inferred the presence of two numerically distinct objects when faced with two different shapes of a rigid entity, but not when faced with different shapes of a non-solid substance.

Infants did not use shape information as a reliable indicator for identity changes in substances. This was appropriate, because it was indeed possible that the experimenter changed the shape of the clay entity from a U-shaped into an I-shaped entity inside the box. Alternatively, it is possible that the performed shape transformation (from U to I) prevented infants from taking the shape of the substance into consideration. Although it needed substantial force to transform the U- into the

I- shaped entity, and the retrieved entity thus retained its shape during the 5-second manipulation period (i.e., no reference to the transformation), the shape change from U to I may not have been salient enough to support substance individuation. That is, numerous studies demonstrated that in order to individuate even rigid objects, infants needed shape differences that are very salient (e.g., change in kind) (e.g., Bonatti et al., 2002; Kingo & Krojgaard, 2011; Van de Walle et al., 2000; Xu & Carey, 1996; Xu & Baker, 2005). We therefore tested a control condition in which a non-solid substance transformed both in shape and in kind.

5.6 Kind Transformation Control

The kind transformation control condition presented infants with a change in shape and kind. That is, in the switch trial, the non-solid substance transformed from a sphere into a star. This may support infants' individuation of substances, since changes in kind appeared to facilitate infants' individuation at least in the case of rigid objects (Kingo & Krøjgaard, 2011; Xu et al., 2004). We hypothesized that infants search longer in switch trials than in no-switch trials if they appreciate that the shape change indicates an identity change in the non-solid substance.

Sixteen infants (8 girls) participated in the control condition (mean age = 365 days, *SD* = 7 days). Four additional infants had to be excluded due to experimenter error (2) and mother interference (2). Again, a second observer coded searching times of half of the infants, and the mean differences between switch and no-switch trials were compared with the codings of the first observer. As the inter-rater agreement was high (r = .98), the first observers' codings were used in the subsequent analyses.

The procedure was identical to the non-solid condition in Experiment 1 except for the shapes of the test stimuli. One test stimulus was a six-pointed star measuring 6 cm in diameter and 2 cm in height; the other stimulus was a sphere measuring 4 cm in diameter. Note that these stimuli were made of the same amount of modeling clay and did therefore not differ in volume.

We obtained similar results as in the non-solid condition of the main experiment. Infants' mean searching time in switch trials was 3.42 s (SD = 3.53) and 2.91 s (SD = 2.06) in no-switch trials. These search times did not differ statistically from each other, $t(15) = .53$, $p = .61$. Also, nonparametric tests revealed no difference between the two trial types. Only 5 children searched longer in switch than no-switch trials, Wilcoxon $z = .03$, $p > .9$ (see also Figure 15). These results suggest that infants did not take the shape transformation as an indicator for the presence of two entities inside the box. It is important to note that—in contrast to the main study— the shape transformation involved here is one that was impossible for the experimenter to have carried out while placing the entity into the box That is, the non-solid substance was not merely *deformed* as in the main study (i.e., two variants of a clay "sausage": a straight and a bent one), but actually *transformed* into a different kind (i.e., a star and a sphere).

5.7 General Discussion

Twelve-month-old infants individuated a rigid object on the basis of a shape change but did not do likewise when faced with a non-solid substance. Consequently, infants in the rigid condition correctly inferred the presence of two numerically distinct objects when faced with two different shapes of a rigid entity, whereas infants in the non-solid condition disregarded this possibility when confronted with analogous stimuli. From these results it can be concluded that infants appreciated that shape invariance is a property restricted to rigid objects. However, despite the fact that the transformation involved a transformation from one entity kind (sphere) to another entity kind (star), infants did not infer the presence of two entities inside the box in the kind transformation control condition. This additional finding suggests that infants' disregarding of shape as a defining characteristic of non-solid substances is of a global nature.

The infants in our study individuated the rigid entity based on the change of a single property (i.e., shape) while all other properties (e.g., color and volume) were held constant. To our knowledge, we are the first to show that infants succeed in individuating objects on the basis of a single property change using a manual-search task. Previous research focusing on infants' use of shape changes for object individuation revealed ambiguous results. While research employing simplified visual and search procedures suggests that infants use shape quite early and primary to other surface features such as pattern, color or luminance (e.g., Needham, 1999; Tremoulet et al., 2000; Wilcox, 1999; Wilcox & Baillargeon, 1998a; Woods & Wilcox, 2006; Xu & Baker, 2005), more complex visual and search measures found that it is not until 12 months (and only on the basis of emerging kind concepts) that infants start to use shape information to individuate objects (e.g., Van de Walle et al., 2000; Xu & Carey, 1996; Xu et al., 1999). Indeed, Xu et al. (2004; see also Kingo & Krøjgaard, 2011) found successful individuation in 12-month-old infants only for cross-kind transformations (e.g., cup-ball), but not for within-kind (e.g., bent bottle-regular bottle) transformations. However, the stimuli used in the rigid condition were unfamiliar to the infants, did not refer to different kinds, and did not activate preexisting knowledge (for instance the kind concept *bottle*). In fact, they were much more comparable to the simple objects (e.g., single-colored, basic shape) used in the simplified procedures.

Furthermore, infants in the present study were supplied with both visual and haptic information. Haptic perception is a very powerful source for perceiving different shapes. Even very young infants manage to distinguish different shapes on the basis of haptic information (see Streri & Gentaz, 2009, for a review). Moreover, multisensory information has been shown to facilitate infants' individuation processes. For example, it supports individuation on the basis of mere color changes (Wilcox, Woods, Chapa, & McCurry, 2007), and affords the recognition of cross-kind shape differences that are not recognized by vision alone (Kingo & Krøjgaard, 2011). The supplementary haptic information might have guided attentional focus to the relevant shape properties in our study. At any rate, our results suggest that infants are able to use shape even in the absence of cross-kind transformations in the case of rigid objects. Still, much more research is needed to clarify the relative impact of task specific characteristics and the role of the emerging kind concepts in the process of object individuation.

Information about material properties of the stimuli was mainly gained during the initial familiarization phase. This is the case because the non-solid test stimuli did not change their shape during the post-retrieval 5-second exploration phase. Yet, despite the identical appearance of the rigid and the non-solid stimuli, infants correctly inferred that only a non-solid entity could change its shape. Thus, they did not interpret the observed shape change as a change in identity. This conforms to previous studies, which found that infants are sensitive to the material properties (i.e., softness) of objects (e.g., Aguiar & Baillargeon, 1998; Baillargeon, 1987; Schweinle & Wilcox, 2004; Walker et al., 1980), and extends them to the ontological class of permanently deformable non-solid substances.

Moreover, the results of the kind transformation control condition add to the existing literature with regards to the nature of infants' representations of the class of non-solid substances. That is, we found that infants did not individuate non-solid substances on the basis of shape despite an evident cross-kind transformation. Many of the previous research examining the ontological origin of the object-substance classification focused on substances that are unbound and shapeless (e.g., liquids and aggregates) (e.g., Gao et al., 2000; Hespos et al., 2009; vanMarle & Wynn, 2011), hence, the very extremes in the object-substance distinction. These substances cannot be individuated unless a non-intrinsic spatiotemporal criterion is provided (e.g., *piles* of sand). However, previous work has demonstrated that infants fail to build individuated representation of such substances even when they are provided with obvious spatiotemporal information (i.e., two separate hiding places) (Huntley-Fenner et al., 2002). Still, in-between the two extremes of rigid objects (e.g., a block of wood) and non-cohesive substances (e.g., sand) are various material entities that vary in the degree by which they offer entity-intrinsic criteria for individuation (e.g., the clay used in the present study). To illustrate, snow can adopt and keep a shape despite being non-solid, therefore offering an intrinsic criterion for individuation.

Consequently, while snow that is molded into the shape of a ball may maintain a "ball-identity" only for a brief moment, it can be represented (at least from an adults' perspective) just as that—a ball. Related to that, the non-rigid substance presented in the study by Huntley-Fenner et al. (2002) provided an intrinsic criterion for individuation because its boundaries remained intact over the course of motion. Indeed, infants were able to build individuated representations of this substance, while they failed to do so in the case of the unbound, non-cohesive sand. However, while this study has shown that infants are able to use spatiotemporal information to build individuated representations of a non-solid bound substance, the present study suggests that infants do not use featural information (i.e., shape) to build individuated representations of a similar substance.

Taken together, our findings add to the body of knowledge on the nature of infants' representations of rigid and non-solid substances. That is, while the representation of a rigid substance entails both spatiotemporal and featural information, the representation of a non-solid substance may well entail spatiotemporal information, but does not entail featural information of shape. It is important to note that disregarding shape is inappropriate in the particular condition of the present study (i.e., kind transformation) as well as disregarding the fact that the transformation was not feasible (i.e., impossibility of forming a sphere into a star in the given time). However, disregarding shape information in the case of a non-solid substance can be regarded as a useful prerequisite for later language acquisition. That is, while the label of a rigid substance is guided by the shape of the substance (e.g., a ball), the label of a non-solid substance is guided by the substance itself, and not the shape of the substance (e.g., snow). Indeed, the study of infants' language acquisition has demonstrated an early sensitivity towards these characteristics of rigid and non-solid substance. That is, young children label rigid substances on the basis of shape information (i.e., extension of an unknown label to an entity with the same shape), whereas they disregard shape in the labeling of non-solid substances. In the latter case, the labeling is indeed based on the substance itself (i.e., extension of an unknown label to an entity that is made of the same substance) (see Papafragou, 2005, for a review).

In sum, infants demonstrated remarkable sensitivity to properties that differentiate non-solid substances from rigid objects. However, many questions concerning the nature of the representation of non-solid substances remain unanswered. Most importantly, if shape is not a defining property of non-solid substances, future studies are needed to determine what properties infants attend to in order to define them. A fruitful way to address this question might be the examination of infants' representation of food, an ecologically highly valid category of non-solid substances (cf. Shutts, Condry, Santos, & Spelke, 2009).

6. OVERALL DISCUSSION

The present thesis has examined the visual and tactile conditions that lead to the representation of physical entities as an individual kind or as a substance kind in infants. While previous research has shown that representations of prototypical members of each of these two classes of physical entities differ fundamentally (e.g., rigid object as individual kind, no substance permanence in the case of sand), the processes that promote these differences are not well understood (e.g., Cheries et al., 2008; Chiang & Wynn, 2000; Huntley-Fenner et al., 2002; Wynn et al., 2002). Furthermore, previous research has demonstrated many parallels between adults' and infants' representations of individual kinds and substance kinds (see Cheries et al., 2009, for a review). However, these parallels are a matter of debate (e.g., Bogartz, Shinskey, & Speaker, 1997; Haith, 1998; Meltzoff & Moore, 1998). The present studies have examined the two main properties that distinguish non-solid substances from rigid objects (i.e., rigidity and cohesion) (Huntley-Fenner et al., 2002; vanMarle & Scholl, 2003) and have aimed to draw parallels between the measurements of infants' representation to tasks used in adulthood (Kahneman et al., 1992; Pylyshyn & Storm, 1988). Table 3 presents the revised positioning of the categories of representation based on the new findings (cf. Table 1). The following sections will now discuss the positioning in terms of the properties of rigidity and cohesiveness.

Table 3

The representation of physical entities as an individual kind or as a substance kind in infant working memory (prolonged occlusion tasks) and in infant and adult attentive tracking (no occlusion tasks)

	Prolonged occlusion	No occlusion
Individual kind		
Small collection	Wynn (1992)	Study 2: 4 individual items
Bound collection	Wynn et al., (2002)	Study 1: group of 4
		Study 2: group of 6
Non-rigid (bound)	Huntley-Fenner et al. (2002)	Study 1
Minor cohesion violation	Cheries et al. (2008)	Adult OSPBs (Mitroff et al., 2004)
	Pilot A: split in 2, Pilot B: split in 3	Study 1: split in 3
Rigidity violation		Study 1: rigid-to-non-rigid
Substance kind		
Granule	Huntley-Fenner et al. (2002)	Adult MOT (vanMarle & Scholl, 2003)
Large collection	Feigenson and Carey (2005)	Study 2: 5 items
Major cohesion violation	Chiang and Wynn (2000)	Study 1, split in 4
	Pilot B, split in 4	
Non-rigid (shape)	Study 3	

6.1 Rigidity

Studies 1 and 3 examined infants' representation of non-rigid entities. The findings of Study 1 complement the existing literature and show that the representation of individual kinds extends to the class of non-rigid substance

(Huntley-Fenner et al., 2002). Eight-month-old infants became habituated to the number of individuated entities, and as a result looked longer at the novel number of entities during test events. This parallels the finding that adult observers tracked non-rigidly moving entities as accurately as rigidly moving entities (vanMarle & Scholl, 2003).

The violation of the rigidity principle (i.e., the loss of rigidity during the course of motion) did not disrupt the infants' tracking process. However, looking times at this event were reliably longer compared to the looking times at the event containing no violation. The transformation from a rigid to a non-rigid entity resembles the events presented by Gibson and co-workers (Gibson et al., 1978; Gibson et al., 1979; Walker et al., 1980). In these, infants dishabituated to a non-rigid motion when they were habituated to a rigid motion beforehand, and vice versa. The longer looking times found in Study 1 might thus have been caused by the fact that each motion of the entity encompassed both habituation and test stimuli (i.e., an individual kind and a substance kind) from the original studies.

In contrast to Study 1, the events in Study 3 involved a prolonged period of occlusion. The fact that infants searched for the hidden non-solid substance inside the box therefore confirms the finding that infants represent non-solid substance as a continuously existing physical entity (Huntley-Fenner et al., 2002). The non-solid substance employed in Study 3 (i.e., modeling clay) is characterized by its ability to adopt a specific shape. However, the shape of modeling clay is transformable and can easily be changed by a mechanical force. That is, shape changes indicating identity changes in rigid objects can be disregarded in the case of a non-rigid substance. The findings of Study 3 suggest that infants are sensitive to these material properties. However, while adults can easily represent individual kinds based on the shape of a substance (e.g., a snowman), the findings of Study 3 suggest that infants' representation of a non-rigid substance never includes shape information. That is, in this case, infants disregarded shape changes in a non-rigid substance even in the cases involving an unfeasible transformation.

Taken together, these results constitute an addition to the previous literature on infants' appreciation of substance as a permanent property of physical entities by demonstrating that this ability extends to the class of non-rigid substance (Aguiar & Baillargeon, 1998; Gibson et al., 1979; Schweinle & Wilcox, 2004). Infants' representation of a rigid substance includes information about its stable shape, whereas there is no shape information tied to the representation of a non-solid substance. However, infants are able to track non-rigid entities in terms of individual kinds on the basis of clear spatiotemporal information (cf. Study 1).

6.1 Cohesion

Studies 1 and 2 examined infants' representation of non-cohesive collections. In line with previous findings, Study 2 demonstrated that 10-month-old infants detected a single object added to a small collection, but failed to detect the additional object in the case of a large collection (Feigenson et al., 2004). However, infants succeeded in identifying the additional object in the case of a large collection by grouping the objects into an overarching figure.

A similar grouping of multiple objects was observed in Study 1. In this study infants were presented with collections of multiple objects undergoing collective movement. Eight-month-old infants were able to track these collections as individuated groups. These findings thus confirm previous reports (Wynn et al., 2002). However, a small methodological change in the event of Study 1 disabled infants from tracking an individuated collection. That is, the infants' tracking process was disrupted if the collection originated from one single object. Previous studies have reported similar losses. That is, infants represented the continued existence of multiple objects as long as these objects were not fragments originating from one single whole (Cheries et al., 2008; Chiang & Wynn, 2000; see also Feigenson & Carey, 2005). In contrast to previous findings, however, cohesion violations disrupted the tracking process only in the case of a split resulting in a large number of fragments (split in four). If the split resulted in a small number of fragments, the following minimums in infants' representation were established: In Pilot Study A (split in two) and in Pilot Study B (split in three) substance permanence; and in addition, in Study 1 (split in three), the uninterrupted tracking of an individual kind.

It is important to note that, based on methodological considerations (i.e., focusing the direction of gazes), a cohesion violation was equally presented in the events in Study 2 (i.e., an initial object split into a multitude of dots). However, this split did not prevent the participants from tracking the resulting dots, at least in the case of a small collection (up to four) and in the case of the large collection numbering six. The success in the case numbering four is surprising given that infants failed to track this number of fragments in Study 1. Several methodological differences between the two studies may have simplified the tracking of the events in Study 2. That is, infants needed to compare two collections of fragments in Study 1, while they were presented with only one collection in Study 2. The representation of two sets may be subject to more severe constraints than one set. Furthermore, the fragments in Study 1 were in constant random motion, while the fragments in Study 2 moved in a straight line towards their final position. The unambiguous motion pattern of the four dots in Study 2 may have prevented infants from a substance kind perception of the dots (i.e., their merging into a mass).

In sum, it was established that individual-based processing may extend to non-cohesive collections, and may be sustainable even in the face of a cohesion violation, at least when the transformation led to a small number of fragments. Given that this finding was replicated in both pilot studies and in Study 1, these findings provide convincing evidence that a cohesion violation in itself is *not* influential enough to disrupt infants' tracking process.

6.2 Conclusion

The findings can be considered as providing evidential underpinnings for three overall conclusions. Whether a physical entity is represented as an individual kind or a substance kind is determined by the spatiotemporal properties in the motion pattern of the entity. Working memory capacities and attentive tracking processes in infancy are related to one another. The indications are that the processes that enable adults' object tracking may likewise govern infants' representation of individuals.

Taken together, the findings of this thesis suggest that individual-based tracking may only apply to visual arrays that contain unambiguous spatiotemporal information. The experiments demonstrated that the motion patterns of non-rigid entities (including violations of rigidity) and non-cohesive collections did not disrupt infants' tracking process. These events enable the observer to identify a distinct location in space and time (e.g., the center of an entity), attend to this location, and track it in motion. By contrast, cohesion violations force the abandonment of a distinct location in space and time. That is, if one object splits into multiple objects, the initially attended location is reassigned to the locations of the resulting fragments (i.e., new space-time allocations need to be performed). Nevertheless, the experiments undertaken also showed that the infants' tracking process—similarly to adults' object tracking (Mitroff et al., 2004)—was in a position to undertake this reassignment in the case involving a small number of resulting fragments (i.e., multiple individuals), but that the reassignment failed if the outcome of the violation resulted in a mass (i.e., no notion of individual kinds), in which case the reassignment does not apply to distinct individual objects.

As opposed to most prior research, a prolonged period of occlusion was included only in Study 3 and in the pilot studies. A direct comparison of the above findings with previous research is therefore limited. Specifically, it is not possible to draw conclusions regarding the representation of the presented entities if infants were required to store them in working memory (cf. Carey & Xu, 2001; Feigenson, 2001). However, the tasks involving occlusion and the tasks involving no occlusion are congruous to the extent that substance permanence (i.e., prolonged occlusion tasks) and individual-based tracking (i.e., non-occlusion tasks) have been demonstrated in the cases of one and the same entities. These congruencies between our own findings and the findings in the external literature, and likewise the overlaps within the two, are outlined in Table 3, and demonstrate that infants successfully build enduring representations in cases where they also succeed in tracking individuated entities, while on the other hand they fail to build enduring representations of entities that they equally fail to track as individuated. This would indicate that infants' working memory capacities and attentional processes are comparable.

Finally, the findings above suggest that similar processes govern infants' and adults' representations of individual kinds and substance kinds. The literature on adults suggests that a process of object-based attention governs these representations. That is, indexes are established for individuals in the visual field, and these indexes are tracked through space (Kahneman et al., 1992; Pylyshyn, 2001). A number of scholars have postulated that a similar process governs infants' representation of individual kinds over periods of occlusion (Carey & Xu, 2001; Feigenson et al., 2004; Leslie et al., 1998; Spelke & Kinzler, 2007). This approach argues that longer looking times at an unexpectedly revealed object indicate that a novel index has to be established for the novel object (Leslie et al., 1998). Yet in general, looking times are measured overall, and not at a distinct location (i.e., the location of the novel object). However, the use of an eye-tracking device in Study 2 enabled a precise measurement of the location of infants' gaze and demonstrated that infants do actually look longer at a novel object in comparison to a familiar one. Furthermore, the findings of Study 1 would indicate that infants' tracking of non-rigid and non-cohesive entities is individual based, which overlaps with similar findings in adults' object-based attention (vanMarle & Scholl, 2003). Study 1 also provides evidence that infants' tracking process is not disrupted by the cohesion violation itself—a finding that has been likewise established in adults' object-based attention experiments (Mitroff et al., 2004). The strongest evidence for a shared mechanism, however, is contained in Study 2, and the clear parallel it demonstrates—using identical events—between infants' and adults' looking patterns.

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ZUSAMMENFASSUNG

Eine physikalische Entität kann in Form eines Individuums oder in Form einer Substanz repräsentiert werden, wobei nur dem Individuum eine Identität zugeschrieben wird. Die vorliegende Arbeit untersuchte diese zwei Arten der Repräsentation einer physikalischen Entität im Säuglingsalter. Zwei zentrale Eigenschaften eines rigiden Objektes, welches typischerweise als Individuum repräsentiert wird, standen dabei im Zentrum: die Rigidität des Objektes als Garant der Formstabilität und die Kohäsion des Objektes als Garant des inneren Zusammenhalts. Nicht-rigide und nicht-kohäsive Entitäten werden jedoch nicht zwangsläufig als Substanz repräsentiert. So können zum Beispiel nicht-solide Substanzen oder kollektive Entitäten als Wassertropfen oder als Vogelschwarm repräsentiert werden. Bereits im Säuglingsalter umfasst die Repräsentation von Individuen neben rigiden Objekte zum Beispiel auch kollektive Entitäten oder verformbare Substanzen (Wynn et al., 2002; Huntley-Fenner et al., 2002). Der Prozess, welcher zu einer individuumsbasierten oder einer substanzbasierten Repräsentation einer Entität führt, ist jedoch unklar.

Drei Studien untersuchten die Auswirkungen von fehlender Rigidität und fehlender Kohäsion auf die Repräsentation physikalischer Entitäten bei 8- bis 12 Monate alten Säuglingen. In den Studien wurden Masse der visuellen Aufmerksamkeit (Blickzeiten in Studie 1, Blickzeiten und Blickrichtung in Studie 2) und handlungsbasierte Masse (manuelle Suche in Studie 3) erhoben. Studie 3 wurde zudem in unveränderter Form mit einer Gruppe Erwachsener durchgeführt.

Aus der Summe der Ergebnisse dieser Studien lassen sich zwei globale Schlussfolgerungen ziehen. Zum einen befähigte eindeutige raumzeitliche Information (z.B. eine klar begrenzte Gruppe) aber nicht Eigenschaftsinformation (z.B. die Form) die Säuglinge, nicht-rigide und nicht-kohäsive Entitäten als Individuen zu repräsentieren. Zum zweiten war die Anzahl Individuen, welche die Säuglinge gleichzeitig repräsentieren konnten, klar begrenzt und grosse Kollektionen wurden als Substanz repräsentiert.

Diese Ergebnisse erweitern die Säuglingsliteratur und zeigen bedeutsame Parallelen zur Repräsentation von Objekten und Substanzen im Erwachsenenalter auf, da auch Erwachsene Individuen primär aufgrund von raumzeitlicher Information generieren und die Anzahl Individuen, welche gleichzeitig repräsentiert werden können, begrenzt ist (vanMarle & Scholl, 2003).

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